11^{th} World Conference on Thermophotovoltaic Generation of Electricity

Thursday, 25 September 2014

Amsterdam, The Netherlands

Program Outline

08:30	Welcome and Introductory Remarks

TPV cells and semiconductor technologies Prof. Zhongfu Yu

08:35	Prof. Ganesh Balakrishnan, University New Mexico, USA, “Epitaxial and non-epitaxial large area thermophotovoltaic cells”
08:50	Jos M. Borrego, Prof. Emeritus RPI, MTPV Power Corp., USA, “Electrical Characteristics and Fabrication Process of N+ and P+ Double diffused IBC GaSb PV Cells interconnected in MIM form”
09:05	Prof. Tom Vandervelde, Tufts University, USA, “Long Wavelength Thermophotovoltaic Diodes”
09:20	Prof. Martin Cryan, University of Bristol, UK, “Diamond Based Solar Thermionic Energy Converters”
09:35	Coffee break

TPV high-temperature photonics Dr. Ivan Celanovic

09:50	(Invited) Prof. Zongfu Yu, University of Wisconsin-Madison, USA, “Controlling far field thermal radiation at the small scale: thermal extraction and superradiant thermal emission”
10:10	Pavel Dyachenko, University of Alberta, CA / TU Hamburg, D, “New frontier for plasmonics and metamaterials: Thermophotovoltaics”
10:25	Prof. Ramon Alcubilla, Universitat Politcnica de Catalunya, Barcelona, Spain, “Silicon- Based Selective Thermal Emitters”
10:40	Veronika Stelmakh, MIT, USA, “Monolithic integrated thermal emitter solutions for high performance TPV systems”
10:55	Veronika Rinnerbauer, Johannes Kepler University Linz, Austria, “Selective absorbers and emitters based on metallic 2D photonic crystals”
11:10	Prof. Tom Vandervelde, Tufts University, USA, “Metamaterial selective emitters for TPV applications”
11:25	Coffee break

TPV Systems and Integration Dr. Veronika Rinnerbauer

11:40 Invited: Walker Chan, MIT, USA, “Millimeter scale, all metallic, high-energy-density thermophotovoltaic generator”

12:00 Prof. Makato Shimuzu, University of Tohoku, JP, “Low concentration solar- thermophotovoltaic systems using monolithic planar absorber/emitter”

12:15 Donald Chubb, MTPV Power Corporation (retired), USA, “Solar Compound PV-TPV Energy Conversion System with Thermal Storage”

12:30 Andrej Lenert MIT, USA, “Role of spectral non-idealities in the design of solar thermophotovoltaics”

12:45 Closing Remarks

Epitaxial and non-epitaxial large area thermophotovoltaic cells

Nassim Rahimi*[1], Andrew A. Aragon[2], Darryl M. Shima[2], Christopher Hains[2], Tito Busani[2], Ganesh Balakrishnan[2], and Luke F. Lester[1]

[1]Virginia Polytechnic Institute and State University, 302 Whittemore Hall, Blacksburg, VA 24061, USA
[2]Center for High Technology Materials, University of New Mexico, 1313 Goddard SE, Albuquerque, NM 87106, USA

Thermophotovoltaic cells have significant potential in efficiently converting thermal energy to electrical energy. These applications include conversion from internal combustion engines, small nuclear sources and even portable fuel-based sources. Group-III antimonide semiconductors have been identified as the material of choice for such TPV devices due to the possibility of growing materials with the bandgap energies of 0.51 eV for quaternary alloys to 0.72 eV for binary GaSb that are correspond to commonly available heat sources. The quaternary alloys are grown epitaxially while the binary GaSb devices can be realized through non-epitaxial techniques.

In this work, we have pursued fabrication and design methods that will allow us to realize large area GaSb-based diode technology for TPV applications. TPV yield is a serious issue in such large area devices. Functional TPV cells using epitaxial GaSb, epitaxial GaInAsSb, and implanted GaSb with areas up to 1 cm2 are realized. The epitaxial cells fabricated in this study allow for the engineering of the bandgap in the structure and also allows for the tailoring of the absorber in the cell to 2.4 m which is a blackbody wavelength of interest. These cells however are not straightforward to scale in dimension due to the presence of large epitaxy related defects that end up shorting the devices. We have identified and mitigated the effect of such shunt defects that were limiting the yield of the epitaxial TPVs on GaSb. The Non-epitaxial TPV cells are realized using beryllium ion implantation into an n-type GaSb substrate. Through the use of rapid thermal annealing a pn junction is formed. The ion-implanted approach is intended to maximize shunt resistance compared to the epitaxial technique. In-depth analysis of the material using transmission electron microscopy, electron dispersive spectroscopy and secondary ion mass spectroscopy is presented and correlated to the electrical characterization results.

*nrahimi@unm.edu

Electrical Characteristics and Fabrication Process of N+ and P+ Double diffused IBC GaSb PV Cells interconnected in MIM form

J.M. Borrego*[1], E. Brown[1], P. Greif[1], A.W.K. Liu[2], and G. Rajagopalan[3]

[1]MTPV Power Corp. Austin, Texas 78728, USA
[2]IQE, Bethelem, PA 18015, USA
[3]UC, Rensselaer, N.Y. 12144

In this paper we present the properties and electrical characteristics of IBC GaSb PV cells fabricated by double diffusion of the N+ and P+ regions. The IBC cells are fabricated on GaSb epi-layers grown on SI-GaAs substrates with the purpose of interconnecting the cells in series to achieve a MIM type of structure.

The paper gives the details of the fabrication of the N+ and P+ regions by S or Se and Zn diffusions, respectively, on the GaSb epi-layer and their electrical characteristics. We describe the process to etch trenches in the GaSb epi-layer with the purpose of isolating each PV cell from each other and the interconnection pattern we have used to increase the output voltage and decrease the photocurrent to decrease series resistance losses but keeping the same output power density.

In the paper we give the electrical performance of the fabricated GaSb PV cells: dark I-V, QE and below bandgap IR reflectance. We present the way we have achieved good spectrum efficiency by the use of Back Surface reflectors without the need of interference filters on the surface illuminated by the Black Body radiation. We give guidelines for the design of the IBC cells to achieve a high QE and low dark current density for increasing the open circuit volage.

*borrego@verizon.net

Long wavelength thermophotovoltaic diodes

Abigail S. Licht[1], Dante F. DeMeo[1], Ahmed Zayan[1], Katherine Levinson[1], and Thomas E. Vandervelde*[1]

[1]The Renewable Energy and Applied Photonics Laboratories, Tufts University, Medford, MA 02155, USA

The conventional thermophotovoltaic diode material is gallium antimonide (GaSb). GaSb, however, with a cut-off wavelength of 1.73m, is optimized for high temperature sources (>1400C). For lower temperature applications, TPV diodes with longer cut-off wavelengths are required to optimally convert the spectrum. Development of these longer wavelength diodes will enable TPV to encompass a wider range of technologies.

Bulk III-V ternary and quaternary compounds, such as InGaAs and InGaAsSb, have much longer cut-off wavelengths than GaSb and have been explored extensively. More recently, the additions of heavier III-V materials, such as thallium and bismuth, have been investigated for long-wavelength TPV. In addition to bulk materials, superlattice structures have been explored. The superlattice material is composed of alternating thin layers of material, in which the bandgap is determined by varying the thickness and periodicity of the constituent layers. These superlattice structures allow for flexibility in band engineering and reduced Auger recombination rates. The most recent progress on these materials is presented here.

(figure)

*tvanderv@ece.tufts.edu

Diamond based solar thermionic energy converters

M. J. Cryan*[1], S. Nunez-Sanchez[1], N. Ahmad[1], C. Wan[1], J. Stokes[1], M. Z. Othman[2], H. D. Andrade[2], J. Harwood[2], I. Bickerton[2], and N. Fox[2]

[1]Dept. of Electrical and Electronic Engineering, University of Bristol, Bristol, U.K.
[2]Schools of Physics and Chemistry, University of Bristol, Bristol, U.K.

Solar thermionics involves the use of incident solar energy to heat a material such that electrons are emitted from the surface and received by a cooled collector to create an electric current. Terrestrial solar-thermionic converters are becoming a viable option as an emerging renewable energy technology due to recent work in lowering the work function of the emitter[1]. The main advantage of this technology is the relatively simple and low cost material requirements compared to photovoltaics and potential high conversion efficiencies achievable when waste heat recovery is included. This paper presents results from a UK project using diamond as both emitter and collector material and explores the use of metal and metal-diamond composites to convert incoming solar energy into heat as efficiently as possible. As with any solar-thermal system it is critical to absorb the maximum amount of incident solar energy whilst preventing energy from being re-radiated by the emitter in the thermal Infra-Red range. In this case it is also critical to prevent heating of the cooled collector which provides an extra level of design challenge. The paper will present results for flat nickel[2] and 1D and 2D patterned nickel films. Preliminary results for bi- and trilayer metasurfaces[3] will be shown along with laser heating experiments carried out at a wavelength of 10um on micron scaled patterned metal surfaces. Preliminary thermionic emission results will also be shown.

[1] N. Fox, T. L. Martin, K. M. O'Donnell, "Low work function diamond surface and radiation energy converters," US Patent App No: 13/304,499, 2013

[2] N. Ahmad, J. Stokes and M. Cryan, "Ultra-Thin Metal Films for Enhanced Solar Absorption," Nano Energy, 1(6), August (2012)

[3] T. Cao, C. Wei, R. E. Simpson, L. Zhang and M. J. Cryan, "Rapid phase transition of a phase-change metamaterial perfect absorber," Optical Materials Express, Vol. 3, No. 8, 1 August 2013

*m.cryan@bristol.ac.uk

Control far field thermal radiation at the small scale: thermal extraction and superradiant thermal emission

Zongfu Yu[1]

[1]Department of Electrical and Computer Engineering, University of Wisconsin, Madison, USA

Efficient thermophotovoltaic cells benefit from advanced manipulation of thermal emission at the small scale. Here we show two interesting effects from our recent works.

First, we show how to use thermal extraction to extract more radiation energy to the far field than the limit of back body.

Second, we show the analog of superradiant emission in thermal emitters, where the coherent effect of thermal radiation causes anomalous scaling law of thermal radiation power.

New frontier for plasmonics and metamaterials: Thermophotovoltaics

P. Dyachenko[1], S. Lang[1], A. Yu. Petrov[1], M. Stormers[2], M. Eich[1], Huan Hu[3], S. Molesky[3], and Z. Jacob*[3]

[1]Institute of Optical and Electronic Materials, Hamburg University of Technology, 21073 Hamburg, Germany
[2]Institute of Materials Research, Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research, Max Planck-Straße 1, 21502 Geesthacht, Germany
[3]University of Alberta, Department of Electrical and Computer Engineering, 9107 - 116 Street, T6G 2V4, Edmonton, Canada

Plasmonics and metamaterials have been used for a multitude of applications ranging from sensing, thermal cancer therapy, sub-diffraction imaging to cloaking. Recently a new frontier of applications for plasmonics and metamaterials was proposed by us: high temperature selective thermal emission for thermophotovoltaics[1]. We will present a detailed description and initial experimental results of engineering thermally excited far field electromagnetic radiation through the use of epsilon-near-zero (plasmonic) metamaterial coatings. We also introduce the concept of high temperature plasmonics using metals like Titanium Nitride to replace conventional metamaterial building blocks (silver and gold) with low thermal stability. Using the approaches presented here, the angular nature, spectral position, and width of the thermal emission can be finely tuned for a variety of heat transfer applications. Our calculations show that these metamaterial emitters near 1500 K can be used as part of thermophotovoltaic devices to surpass the Shockley-Queisser conversion efficiency limit of 41%. Our work paves the way for a new direction of application for plasmonics and metamaterials: high temperature nanophotonics.

[1] Molesky, S., Dewalt, C. J. Jacob, Z. "High temperature epsilon-near-zero and epsilon-near-pole metamaterial emitters for thermophotovoltaics." Opt Express 21, A96A110 (2013).

*zjacob@ualberta.ca

Silicon-based selective thermal emitters

R. Alcubilla*[1,2], M. Garín[1,2], D. Hernández[1,2], and T. Trifonov[1,2]

[1]Grup de Recerca en Micro i Nanotecnologies, Departament dEnginyeria Electrnica, Universitat Politcnica de Catalunya, Jordi Girona 1-3, Mdul C4, 08034, Barcelona, Spain
[2]2 Centre de Recerca en Nanoenginyeria, Universitat Politcnica de Catalunya, Pascual i Vil 15, 08028, Barcelona, Spain

Selective thermal emitters radiate in a spectrum narrower than a greybody helping to increase the efficiency of TPV systems and are key elements defining the overall system efficiency and power throughput. In addition, the emitter has to withstand high temperatures for long operation times. Here, we review the control of IR radiation through macroporous-silicon structures. Macroporous silicon allows the fabrication of 3D photonic crystals on large surfaces (full wafer surface) with great finesse. The fabricated structures are monocrystalline, as the original wafer, and can be thermally stable at temperatures close to the melting point of silicon under the appropriate ambients. Finally, we present silicon/metallic structures where the macroporous silicon is used as scaffold conformally covered with a thin metallic layer. That way the final structure benefits from both the high thermal stability of the scaffold and the good selectivity similar to full metallic structures.

*ramon.alcubilla@upc.edu

Monolithic integrated thermal emitter solutions for high performance TPV systems

V. Stelmakh*[1], W. R. Chan[1], J. J. Senkevich[1], V. Rinnerbauer[2], M. Soljačić[1], J. D. Joannopoulos[1], and I. Celanovic[1]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Institute for Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria

Microstructured thermal emitters and absorbers based on refractory metals are promising candidates to achieve the high spectral selectivity crucial for high temperature TPV applications. Selective emitters have been studied and fabricated on single crystal tungsten (W) bulk substrates as well as polycrystalline tantalum (Ta) bulk substrates. In TPV systems, bulk emitters must be welded directly on the source of heat and add weight to the system. A single monolithic integrated TPV emitter requires less material, decreasing the fabrication and post-fabrication complexity and integration cost, as well as eliminating the gap between the heat source and emitter leading to reduced edge parasitic loss and optimum thermal contact. In this contribution we focus on spectrally selective emitters that facilitate system integration in TPV applications.

Two solutions are proposed: First, a selective emitter fabricated on Ta-3%W, a bulk substrate engineered to meet the material requirements of the system at the expected high operating temperatures. The Ta-W solid solution alloy combines the better thermo-mechanical properties of W with the more compliant material properties of Ta, allowing a direct system integration path, i.e. machining and welding. In addition, the mechanical stability of the selective emitters is enhanced at high temperatures using Ta-W alloy substrates compared to pure Ta. This is beneficial for overall system stability where degradation such as creep and deflection can play a critical role in system failure. Second, a Ta coating is investigated as a functional layer on different substrates, selected and matched to the system's needs, decoupling the requirements of the functional layer and the substrate. Inconel is chosen as a substrate since it is a readily available low-cost nickel-chromium-based superalloy used in many high-temperature applications.

*stelmakh@mit.edu

Selective solar absorbers/emitters based on metallic 2D photonic crystals

V. Rinnerbauer*[1], E. Lausecker[1], F.Schäffler[1], Y. X. Yeng[2], W. R. Chan[2], V. Stelmakh[2], J. J. Senkevich[2], A.Lenert[2], D. M. Bierman[2], E. N. Wang[2], J. D. Joannopoulos[2], M. Soljačić[2], and I. Celanovic[2]

[1]Johannes Kepler University, Linz, Austria
[2]Massachusetts Institute of Technology, Cambridge, MA, USA

Spectrally selective components are critical elements for solid-state thermal-to-electrical energy conversion, such as thermophotovoltaics (TPV), solar thermophotovoltaics and solar-thermal systems. The key to obtaining high efficiency in this class of high temperature energy conversion is the spectral and angular matching of the radiation properties of an emitter to those of an absorber. Metallic photonic crystals (PhCs) offer the ability to tailor the photonic density of states, which allows for the efficient design of such highly selective and highly efficient emitters and absorbers.

We present a high-temperature stable, integrated double-sided absorber/ emitter pair based on 2D PhCs fabricated on a single flat Ta substrate. These PhCs show tunable and high spectral selectivity and are optimized for a solar TPV system for high operating temperatures ($\geq$1200 K). We show that at these temperatures the high selectivity achieved by the PhC absorber and emitter is crucial to achieve high conversion efficiencies.

Moreover, we propose a solar absorber based on a PhC superlattice design achieving broadband high absorptivity and maximum thermal transfer efficiency for high solar concentrations. The proposed fabrication route by nanoimprint lithography facilitates precise microscopic control of the nanophotonic structures while at the same time it is easily scalable to large areas.

*veronika.rinnerbauer@jku.at

Metamaterial selective emitters for thermophotovoltaic applications

Nicole Pfiester*[1], Norihito Naka[1], and Thomas E. Vandervelde[1]

[1]The Renewable Energy and Applied Photonics Laboratories, Tufts University, Medford, MA 02155

Applying thermophotovoltaic (TPV) technologies to existing energy generation sources allows us to increase energy output while utilizing present infrastructure by reclaiming the heat lost during the production process. In order to maximize the efficiency of these sources, the conversion efficiency of the TPV system needs to be optimized. Novel structures known as metamaterials have been used to create selective-emitters that tailor the incident light spectrum to the band gap of the diode in question, offering the potential to reduce diode heating and increase efficiency. In this talk, we report on the progress made on bringing this technology from the theoretical realm into a usable, thermally robust device. Usage of conducting metals such as platinum and iridium make emitters able to withstand the high temperatures required to create ideal spectra for III-V cells. Surface treatments such as capping layers and varied dielectrics can further extend the operational temperatures for these emitters by helping to prevent degradation.

*tvanderv@ece.tufts.edu

A millimeter scale, all metallic, high-energy-density thermophotovoltaic generator

W. R. Chan*[1], V. Stelmakh[1], B. Wilhite[2], J. J. Senkevich[1], M. Soljačić[1], J. D. Joannopoulos[2], and I. Celanovic[2]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Texas A&M University, College Station, TX, USA

Thermophotovoltaics is a promising technology for portable power generation, but has been traditionally limited to relatively modest efficiencies. Recent advances in two-dimensional photonic crystals promise high spectral efficiency and power densities approaching that of blackbody. However, these have proven difficult to integrate into a system. A novel metallic platform was developed to allow the integration of a tantalum photonic crystal. The metallic platform is comprised of an Inconel microburner and a tantalum photonic crystal. The Inconel microburner has a catalyst-loaded meandering channel, and was fabricated by standard machining. The tantalum photonic crystal has a periodic array of holes arranged in a square lattice and was fabricated by interference lithography and standard semiconductor fabrication techniques. Integration of the two components was achieved by electron beam welding. In this work, we present design and characterization of the metallic platform.

*wrchan@mit.edu

Low concentration solar-thermophotovoltaic systems using a monolithic planar absorber/emitter

Makoto Shimizu[1], Asaka Kohiyama[1], Fumitada Iguchi[1], and Hiroo Yugami[1]

[1]Graduate School of Engineering, Tohoku University, Japan

In this study, we focused on solar-thermophotovoltaic (STPV) systems which use concentration solar power as a heat source. This system is regarded as a kind of photon-photon conversion system. Therefore, to attain high emitter temperature for highly spectral matching with low input power is important to obtain high efficiency. From this perspective, the monolithic planar absorber, which has absorber and emitter on single substrates front and back side, is considered to be essential for this system because its surface area is smaller than the conventional cavity type absorber/emitter. However, the optical losses of the planar type absorber/emitter are larger than that of the cavity type one. Therefore, it is required to control thermal radiation spectrum from both absorber and emitter surfaces for efficient photon-photon conversion. In this study, multilayer coatings are applied to absorber and emitter to control thermal radiation spectrum. Power generation tests are conducted using this absorber/emitter and gallium antimonide TPV cell. The highest system efficiency of 8.3% considering view factor of 0.06 between the emitter and the TPV cell is obtained at 1640 K with concentration ratio of 450 sun.

Solar compound PV-TPV energy conversion system with thermal storage

Donald M. Chubb[1]

[1]MTPV Power Corporation (retired)

This study considers a solar powered energy conversion system consisting of a cassegrain concentrator, a GaAs photovoltaic (PV) array at the secondary of the cassegrain and a thermophotovoltaic (TPV) system with thermal energy storage at the focus of the secondary. The analysis models the GaAs array using measured cell properties. All the major thermal losses are included. Concentrator optics are included using assumed efficiencies. Because of its melting point (1687 K) and very large heat of fusion (1802j/gm) silicon (Si) is used as the thermal storage material. The melting and solidifying of the Si is modeled using a one dimensional thermal conduction analysis. Total energy conversion efficiencies greater than 15% are calculated with 2-6 hours of operation in the dark. For the TPV part of the system, a micro-gap TPV energy converter is assumed.

Role of spectral non-idealities in the design of solar thermophotovoltaics

Andrej Lenert[1], David M. Bierman[1], Veronika Rinnerbauer[1,2], Youngsuk Nam[1,3], Ivan Celanovic[1], M. Soljačić[1], and Evelyn N. Wang[1]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Institute for Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria
[3]Kyung Hee University, Korea

We present the design and development of a nanophotonic solar thermophotovoltaic (STPV) that harnesses the full spectrum of the sun, in a solid-state and scalable way. Through device optimization and control over spectral properties at high temperatures (∼1300K), a device that is 3 times more efficient than previous STPVs is demonstrated. To achieve this result, a framework was developed to identify which parts of the spectrum are critical and to guide the design of nanostructured absorbers and emitters for STPVs. The work elucidated the relative importance of spectral properties depending on the operating regime and device geometry. Carbon nanotubes and a silicon/silicon dioxide photonic crystal were used to target critical properties in the high solar concentration regime; and two-dimensional metallic photonic crystals were used to target critical properties in the low solar concentration regime. A versatile experimental platform was developed to interchangeably test different STPV components without sacrificing experimental control. In addition to demonstrating significant improvements in STPV efficiency, an experimental procedure to quantify the energy conversion and loss mechanisms helped improve and validate STPV models. Using these validated models, we present a scaled-up device that can achieve 20% efficiencies in the near term.