NREL/CP-413-6186
DE-94011831

Proceedings

The First NREL Conference

on

Thermophotovoltaic

Generation of Electricity

July 24-27, 1994

Copper Mountain, Colorado

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Monday, July 25, 1994
8:30am - 10:15am

Session I

Current Status of TPV Conversion

Session Chairman

Tim Coutts

Notes:

Monday, July 25, 1994
8:45am - 9:15am

Experimental Assessment of Low-Temperature Voltaic Energy Conversion

Paul Baldasaro

Notes:

Experimental Assessment of Low Temperature Voltaic Energy Conversion

Paul F Baldasaro, Edward J Brown, David M Depoy,

Brian C Campbell, Josef R Parrrington

Knolls Atomic Power Laboratory Inc., Schenectady New York

Abstract. An experimental investigation of low temperature thermo photo voltaic (TPV) power conversion has been completed in the temperature range of 800°C - 1000°C. Experimental results include: 1) current-voltage characteristics of Indium-Gallium-Arsenide (InGaAs) cells with bandgaps ranging from .73 ev to .52 ev, 2) spectral control characteristics of dichroic interference and semiconductor plasma filters, and 3) design and operational characteristics of a 50 watt TPV power module. Analysis results are presented to demonstrate understanding of process physics. Results support the feasibility of low temperature TPV energy conversion.

Notes:

Monday, July 25, 1994
9:15am - 9:45am

Thermophotovoltaic Electric Generator Using a Hydrocarbon Burner

Lewis Fraas

Notes:

THERMOPHOTOVOLTAIC ELECTRIC GENERATOR USING HYDROCARBON BURNER

Lewis M. Fraas
JX Crystals, Inc.*
Issaquah, WA

Michael R. Seal
Vehicle Research Institute
Bellingham, WA

We have now successfully designed, built, and operated a new quiet lightweight clean electric power generator in which a fuel is continuously burned in a central tube, the tube glows red hot, and photovoltaic cell strings receive the infrared (IR) from this emitter and convert it to electric power. In effect, photovoltaic cells (more commonly referred to as "solar" cells) are used with a small manmade "sun" created by burning natural gas. Because fuel is burned continuously without periodic explosions, our novel thermophotovoltaic (TPV) unit is very clean, quiet, efficient, and lightweight. This technology is very promising as a power source for electric vehicles.

Our novel thermophotovoltaic generator uses new gallium antimonide (GaSb) cells fabricated by JX Crystals. These new GaSb cells are much more sensitive in the IR than traditional silicon solar cells. Our prototype generator uses eight water cooled GaSb circuits each of which produces 3 Volts at maximum power. The eight receivers are arrayed around the central IR emitter / burner . The IR emitted passes through eight lantern windows to the eight receivers. IR filters are located in the lantern windows. These IR filters allow useful shorter wavelength IR to pass through to the cell receivers while reflecting longer wavelength IR back to the emitter to recycle the heat.

Each 3 V receiver contains nine GaSb cells originally designed for point focus solar applications. The active area of each cell is 0.2 cm2. After fabrication, each of the 8 receivers was tested and produced between 2.5 and 3.5 Watts at maximum power. Two groups of four receivers were series connected to produce 12 Volts and approximately 20 Watts. The resultant generator then produced enough power to operate a small television. The result was the world's first thermophotovoltaic generator successfully integrating IR sensitive photovoltaic cells with a natural gas fired IR emitter. We are now in the process of increasing the power from this unit by using (1) cells with 4 times the active area, (2) a higher temperature silicon carbide emitter, and (3) a heat exchanger to couple the exhaust heat into the supply air.

* Patents pending

Notes:

Monday, July 25, 1994
9:45am - 10:15am

GRI Research on Thermophotovoltaics

Kevin Krist

Notes:

GRI Research on Thermophotovoltaics

Dr. Kevin Krist
Gas Research Institute

The Gas Research Insitute (GRI) is sponsoring basic research on natural gas fired radiant structures for:

- Improved porous ceramic and metallic radiant burners used in industrial and commercial heating and drying applications
- Combined radiant structure/photovoltaic cell systems which produce thermophotovoltaic (TPV) power.

TPV is one of a few candidates for residential and commercial auxiliary power for natural gas appliances because of its compactness, quiet operation, modularity, and potential for low maintenance (due to a lack of moving parts). Potential auxiliary power applications of TPV include: self-powered furnaces, power outage or furnace add-on appliances, self-powered water heaters, self-powered absorption cooling, microwave/convective food drying, fireplace power devices, and pipeline cathodic protection. Technical breakthroughs might also result in TPV systems with high enough efficiency for cogeneration applications.

The radiant emitter is a critical component of a TPV system. Radiant structures producing either broadband or wavelength selective radiation are possible. Broadband emitters produce higher radiant fluxes for a given fuel rate. However, Tecogen - GRI's contractor - is currently focusing on the use of selective emitters because of the difficulties of broadband emitters in avoiding excessive heat dissipation in the PV cells.

Selective emitters produce relatively large fractions of radiant output at wavelengths that are closely matched with the bandgap of the PV cell. Optimization of radiant flux for the band gap and area of the PV cells used suggests that emitter temperatures should be above 1400°C. Commercial porous radiant burners for heating applications by contrast typically operate at about 1000°C. However, Tecogen has developed a large, supported, continuous fiber radiant structure based on gas mantle concepts that can produce selective radiation and operate up to temperatures of 1700°C with good thermal shock resistance and rapid response time. Current research is attempting to achieve a 300 W TPV prototype for a self-powered furnace, develop low-cost methods for emitter fabrication, characterize radiant structure life and degradation modes, and evaluate TPV technology.

Notes:

Monday, July 25, 1994
10:45am - 12:00pm

Session II

TPV Tutorials Session

Session Chairman

Richard Schwartz

Notes:

Monday, July 25, 1994
10:45am - 11:10am

Photovoltaic Principles Used in Thermophotovoltaic Generators

Peter Iles

Notes:

PHOTOVOLTAIC PRINCIPLES USED IN THERMOPHOTOVOLTAIC GENERATORS

P. A. Iles
Applied Solar Energy Corporation
City of Industry, California

The paper reviews the basic PV principles, and describes their use in designing TPV generators. The sequence of presentation is as follows:

- Review the main PV concepts (intrinsic excitation, charge collection, voltage barrier and external circuit).
- Describe the range of available thermal radiation sources (blackbodies at various temperatures, selective emitters and use of selective filters).
- Discuss the influence of the source characteristics on the selection of suitable PV materials (best bandgap, and selection of material growth and processing methods).
- Describe the main PV cell fabrication steps (voltage barrier formation, contacts, grid design, coatings and back surface processing).
- Discuss the operating performance (conversion efficiency, output power density, heat transfer and stability).

Notes:

Monday, July 25, 1994
11:10am - 11:35am

Thermophotovoltaic Emitter Development

Robert Nelson

Notes:

THERMOPHOTOVOLTAIC EMITTER DEVELOPMENT*

Robert E. Nelson

Tecogen Division
Thermo Power Corporation
45 First Avenue
Waltham, MA 02254-8995

ABSTRACT

Emitters must be stable, capable of surviving thermal stress, and able to provide tailored radiant output in thermophotovoltaic (TPV) energy conversion systems. Appropriate material systems and proper emitter geometries may be combined to enhance the conversion of thermal energy into useful (photoconvertible) radiant energy. This presentation will begin with a brief history of the development of flame-powered light sources. Certain parts of this early technology are applicable to current high performance emitters for TPV systems, and these features will be pointed out. The role of rare earth oxides in selective emitters will be covered. Structures that are mechanically durable and operate at high fuel rates will be described, and methods of incorporating these emitters in practical power generation systems will be included.

*This work has been supported by the Basic Research Group of the Gas Research Institute, Chicago, Illinois.

Notes:

Monday, July 25, 1994
11:35am - 12:00pm

Mechanical Behavior of Reticulated Ceramics

David Green

(paper not available at time of print)

Notes:

Monday, July 25, 1994
1:30pm - 3:30pm

Session III

Heat Source and Emitter Technologies

Session Chairman

Guido Guazzoni

Notes:

Monday, July 25, 1994
1:30pm - 1:50pm

Silicon Carbide Emitter and Burner Elements for a TPV Converter

Udo Pernisz

Notes:

Abstract

submitted to the

First NREL Conference on
Thermophotovoltaic Generation of Electricity

24-27 July 1994, Copper Mountain, CO

Silicon Carbide Emitter and Burner Elements for a TPV Converter

Udo C. Pernisz and Chandan K. Saha
Dow Corning Corporation, Midland, MI 48686

SiC bulk material is manufactured in the desired shape from an organosilicon-based pre-ceramic polymer by pyrolysis at temperatures >2000 °C. For an evaluation prototype, an emitter was made in form of a 7" tube with 1.5" diameter for operation at 1400 °C ... 1700 °C in conjunction with a GaSb photovoltaic cell (E_g=0.67 eV). The emissivity of the SiC material in this temperature range was determined between 1 µm and 2.5 µm, both total and spectrally resolved. For the design of the burner element the use of SiC material was also investigated.

A discussion of the materials data, the structure and design considerations, and an economic analysis of a SiC-based TPV converter will be presented.

Notes:

Monday, July 25, 1994
1:50pm - 2:10pm

An Experimental Investigation of Hybrid Kerosene Burner Configurations for TPV Applications

Kenneth Schroeder

Notes:

AN EXPERIMENTAL INVESTIGATION OF HYBRID KEROSENE BURNER CONFIGURATIONS FOR TPV APPLICATIONS

K. L. Schroeder, M. F. Rose and J. E. Burkhalter

Space Power Institute
Auburn University, AL

Abstract

A key element in thermophotovoltaic power generation is the development of a compact and efficient configuration for the thermal source and emitter. The present work investigates a hybrid configuration composed of a liquid fuel diffusion type burner utilizing the emitting or radiation structure as the combustion chamber. Hence, two primary elements must be addressed; the complete combustion of the fuel, and effectively using the thermal energy produced to heat the emitter. Overall efficiency is a result of the product of the component efficiencies. Therefore, the maximum obtainable system efficiency will depend on the functional relationships between the individual system elements, and will not necessarily correspond to the maximum obtainable component efficiencies. In this type of configuration the gas dynamics and combustor geometry are the predominant factors, and are therefore the focus of this work.

A small test facility has been set up for the evaluation of various burner/mantle configurations. The prototype burner operates on kerosene at fuel flow rates up to 1.0 kg/hr. Fuel is atomized using an 78 kHz ultrasonic nozzle with multifuel capabilities. Combustion is stabilized and heat transfer is enhanced via forced recirculation interior to the mantle structures. These structures ranging in size from 300 to 1200 cm^3 and are porous in nature. This paper presents an introduction to issues specific to the use of small scale liquid fuel burners for TPV applications, and burner performance data for a series of configurations, in terms of combustor space heating rate or maximum mass loading, and surface temperature distribution.

Notes:

Monday, July 25, 1994
2:10pm - 2:30pm

Porous Ceramic Regenerative Burner for Use in Lower Temperature (<1500 C) TPV Systems

Darryl Noreen

Notes:

R & D TECHNOLOGIES, INC.

551 Observer Hwy., #10B • Hoboken, NJ 07030

ABSTRACT
on
Paper to be presented at
"The First NREL Conference on TPV Generation of Electricity"

Authors: Darryl L. Noreen: President, R&D Technologies, Inc. &
Dr. Honghua (Henry) Du: Stevens Institute of Technology
Materials Science and Engineering

Paper Title: Porous Ceramic Regenerative Burner for Use in Lower Temperature (<1500 C) TPV Systems

R&D Technologies, Inc. (RDT) is developing a thermophotovoltaic (TPV) technology based on use of a porous ceramic regenerative burner capable of producing substantially lower emissions than alternative TPV systems. The burner under development utilizes highly porous ceramics thereby providing low pressure drop coupled with high radiant emission and ultra-low levels of NOx. The current challenge for the development of reliable TPV systems is tied directly to the need for lower cost photocells and the availability of longer life thermal shock resistant porous ceramics that can operate reliably in highly oxidizing, high temperature natural gas combustion environments. In the past, TPV design approaches have focused primarily on use of high temperature (1500 - 2000 C) emitters coupled with silicon photocells. The advent of the III-V photocell technologies make possible development of lower temperature (1000 - 1500 C) TPV systems which should have improved reliability and longer life. This paper will address the current and planned program activities at RDT that are focused on the development and application of regenerative radiant ceramic burners for use in lower temperature TPV systems.

Currently, ***long-lived*** porous (or fibrous) ceramic materials useful for TPV applications are not available for use at high temperatures in oxidizing environments. Porous ceramics will be required to operate continuously at temperatures of 1500 C or higher. Therefore, this project will investigate use of various new ceramic materials and fabrication technologies that could lead to improvements in porous ceramic media durability and life at the required higher operating temperatures. Gaseous fuel combustion within appropriate inert porous ceramic media can produce very low emissions if the combustion takes place within the media (rather than on the surface) and at a low enough temperature. A burner is being developed that takes advantage of this concept. In addition, the burner will utilize regenerative heat recovery to enhance thermal efficiency. Early conclusions regarding materials investigations and fabrication technologies identified will be reported on in this paper. A combustor design concept will be described based on early findings. As part of a recently awarded SBIR Phase I program, an experimental burner will be built and tested by the end of 1994. Future plans (beyond 1994) will also be described.

Laboratory: 614 River Street • Hoboken, NJ 07030

Notes:

Monday, July 25, 1994
2:30pm - 2:50pm

Co-Generation of Electricity and Heat From Combustion of Wood Powder Utilizing Thermophotovoltaic Conversion

Lars Broman

Notes:

Abstract submitted to The First NREL Conference on Thermophotovoltaic Generation of Electricity, July 24-27, 1994, Copper Mountain, Colorado, USA

Co-generation of electricity and heat from combustion of wood powder utilizing thermophotovoltaic conversion

*Lars Broman**
National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401-3393, USA; lbr@t.hfb.se

Jorgen Marks
Dept. of Operational Efficiency, Swedish Univ. of Agricultural Sciences, S-776 98 Garpenberg, SWEDEN

Sweden's most promising renewable energy source for substantial growth during the next decade is biomass, especially from trees. It is believed that the present bioenergy ratio of 15 % of the country's total energy use may double within 10-15 years. Several different wood fuels are used: processed fuels as chunks, chips, pellets, etc. The most refined fuel, wood powder, has been successfully used for several years. While being somewhat more expensive to produce than other wood fuels, it has certain advantages such as cheaper and more efficient combustion. Wood fuel has a high energy density, 18.3 MJ/kg dry matter, and it is combustible also in existing oil furnaces (in the range 1-15 MW) with little alteration [1].

In principle, wood powder would be a possible fuel for small scale combustion, and we are in the process of developing such a furnace. Reliable feeding, and flame ignition and control, are just some of the mechanisms that have to be developed. During the last few months, we have constructed and tested a feeding mechanism and a combustion chamber that seem very promising. We manage to keep a 10 kW flame steadily burning for several minutes at the time.

When used in connection with TPV cells, the powder must be burned in such a way that most of the energy is released as radiation rather than as hot exhaust gases, and that the temperature is sufficiently high. Our temperature goal is 1500 K, a compromise between most useful emitter spectrum and low NO_X production. As of 2 May 1994, we have reached 1446 K in one of our two prototype burners. The next step in the development process is to further increase the radiation fraction, and direct the hot exhausts through an radiative emitter. Selective emitters suited for TPV converters are being developed by Nelson et. al. [2] and by Chubb et. al. [3].

A Swedish TPV R&D program is in the planning, aiming at co-generation of electricity and heat from refined wood fuel [4]. Many components of the TPV converter; combustion chamber, emitter, dichroic filter, and TPV cell mounting and cooling, are considered. Close cooperation with researchers at NREL, working on thin film TPV cell development, is an important aspect of the program.

References

1. J. Marks. Wood powder: an upgraded wood fuel. Forest Prod. J. 42(1992)52-56.
2. R. E. Nelson. Fibrous emissive burners; selective and broad band. Gas Res. Inst. Rpt. GRI-93/0384.
3. D. L. Chubb and R. A. Lowe. Thin-film selective emitter. J. Appl. Phys. 74(1993)5687-98.
4. L. Broman. Cogeneration of electric power and heat from combustion of refined wood fuel by means of thermophotovoltaic conversion TPV. SERC Project Plan (1994).

* Permanent address Solar Energy Research Center, Box 10044, S-781 10 Borlaenge, SWEDEN

Notes:

Monday, July 25, 1994
2:50pm - 3:10pm

Radioisotope Thermophotovoltaic System Design and Its Application to an Illustrative Space Mission

A. Schock

Notes:

RADIOISOTOPE THERMOPHOTOVOLTAIC SYSTEM DESIGN AND ITS APPLICATION TO AN ILLUSTRATIVE SPACE MISSION

A. Schock and V. Kumar
Fairchild Space and Defense Corporation
Germantown, MD 20874 U.S.A.

Abstract

The paper describes the results of a DOE-sponsored design study of a radioisotope thermophotovoltaic generator (RTPV), to complement similar studies of Radioisotope Thermoelectric Generators (RTGs) and Stirling Generators (RSGs) previously published by the author. Instead of conducting a generic study, it was decided to focus the design effort by directing it at a specific illustrative space mission, Pluto Fast Flyby (PFF). That mission, under study by JPL, envisages a direct eight-year flight to Pluto (the only unexplored planet in the solar system), followed by comprehensive mapping, surface composition, and atmospheric structure measurements during a brief flyby of the planet and its moon Charon, and transmission of the recorded science data to Earth during a post-encounter cruise lasting up to one year.

Because of Pluto's long distance from the sun (30-50 A.U.) and the mission's large energy demand, JPL has baselined the use of a radioisotope power system for the PFF spacecraft. RTGs have been tentatively selected, because they have been successfully flown on many space missions, and have demonstrated exceptional reliability and durability. The only reason for exploring the applicability of the far less mature RTPV systems is their potential for much higher conversion efficiencies, which would greatly reduce the mass, and cost of the required radioisotope heat source. Those attributes are particularly important for the PFF mission, which - like all NASA missions under current consideration - is severely mass- and cost-limited.

The paper describes the design of the radioisotope heat source, the thermophotovoltaic converter, and the heat rejection system; and depicts its integration with the PFF spacecraft. A companion paper presented at this conference presents the results of the thermal, electrical, and structural analysis and the design optimization of the integrated RTPV system. It also discusses the programmatic implications of the analytical results, which suggest that the RTPV generator, when developed by DOE and/or NASA, would be quite valuable not only for the PFF mission but also for other future missions requiring small, long-lived, low-mass generators.

Notes:

Monday, July 25, 1994
3:10pm - 3:30pm

Analysis of Solar Thermophotovoltaic Test Data from Experiments Performed at McDonnell Douglas

Ken Stone

Notes:

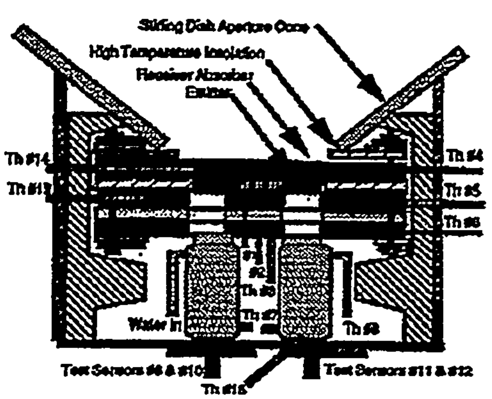
Analysis of Solar Thermophotovoltaic Test Data From Experiments Performed At McDonnell Douglas

by
K. W. Stone
S. M. Kusek
R. E. Drubka
McDonnell Douglas
5301 Bolsa Ave
Huntington Beach, Calif. 92647

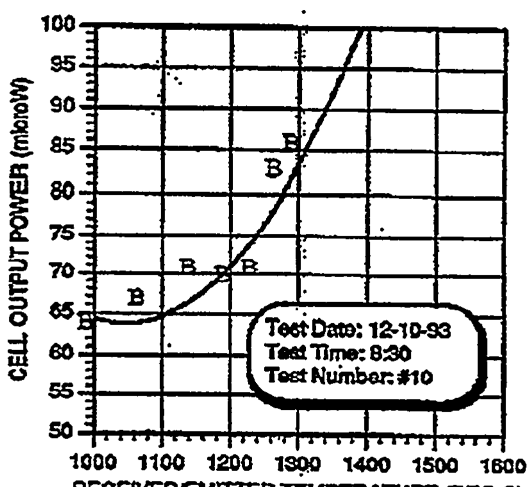
T. D Fay
21911 Bacalar
Mission Viejo, Calif. 92691

Abstract

Solar thermophotovoltaic power systems offer potentially high system efficiency of solar energy to electrical energy conversion and attractive system advantages. McDonnell Douglas Aerospace (MDA) has been investigating this technology for both space and terrestrial applications for several years. A prototype experimental model was designed, built, and tested on a 90 kW_t dish concentrator in the MDA solar test facility. Twelve experiments were conducted with this prototype model with absorber temperatures in excess of 1300° C being achieved using only a fraction of the reflected power from the 90 kW_t dish concentrator. This paper discusses the solar thermophotovoltaic prototype unit, test data, and presents an analysis of the unit's performance A combination of theoretical analysis and test data is used to obtain an understanding of the system and subsystem performance. The preliminary results of these tests that have been conducted and of this analysis indicate that a solar thermophotovoltaic power systems can achieve high system performance. Furthermore this can be demonstrated at the present time with a combination of current off-the-shelf hardware components and components currently being tested in the laboratories.



Design of the STPV test prototype.



Peak Output Power for J12 Sensor.

Notes:

Tuesday, July 26, 1994
8:15am - 10:00am

Session IV

Advanced TPV Devices

Session Chairman

John Benner

Notes:

Tuesday, July 26, 1994
8:15am - 8:30am

Vertical Multi-junction Cells for Thermophotovoltaic Conversion

Bernard Sater

Notes:

Abstract of Proposed Paper for the First NREL Conference on Thermophotovoltaic Generation of Electricity; July 24-27, 1994; Copper Mountain, Colorado:

Vertical Multi-junction Cells for Thermophotovoltaic Conversion

by

Bernard L. Sater
PhotoVolt, Inc.
9007 Westlawn Blvd.
Olmsted Falls, OH 44138

Energy conversion can be very efficient in a thermophotovoltaic (TPV) system where the emitted radiation is near the bandgap energy of the photovoltaic (PV) cells. Intrinsic efficiencies greater than 50% are possible with near bandgap radiation at high power densities with ideal cell designs.

Our vertical multi-junction (VMJ) cell is an integrally bonded, series-connected array of miniature vertical junction p+nn+ unit cells. The VMJ cell structure is ideally suited for providing efficient TPV conversion with indirect semiconductors like silicon or germanium. Its inherent high voltage and low series resistance characteristics are important for high power density applications. Furthermore, the VMJ cell vertical junctions give equal probability to current collection of excess carriers generated at any depth from the illuminated surface. This feature improves the spectral response for near-bandgap energy photons. By incorporating a non-absorbing reflecting back surface, the photo-generation path is doubled and unusable low-energy photons are reflected back toward the emitter to improve overall thermal efficiency. The paper fully discusses major design features of the VMJ cell for efficient TPV conversion.

A proof of concept demonstration of the VMJ cell technology as a high intensity solar cell for terrestrial PV concentrator applications was recently carried out by the author under a NIST/DOE Energy Related Invention Program grant. High intensity flash testing on experimental test devices were conducted at NASA Lewis Research Center in Cleveland, Ohio. Data taken on a 23 junction VMJ cell at 332 AM1.5 suns intensity (33.2 W/cm^2) is summarized in the table. (Solar efficiencies around 25% are anticipated at 500 AM1.5 intensity with prototype development.) The test data shows the high voltage and low series resistance characteristics and high efficiency potential essential for high power density TPV applications.

VMJ Cell Flash Data

23 junctions silicon cell, 0.4922 cm^2 active area (0.0214 cm^2 unit cell area)
Isc = 0.72985 ma @ one sun AM1.5

Intensity - AM1.5 suns	331.77
Voc - volts	16
Isc - ma	242.1
Pmax - watts	3.13
Fill Factor - %	80.8
Efficiency - %	19.19

Notes:

Tuesday, July 26, 1994
8:30am - 8:45am

$In_xGA_{1-x}AS$ Thermophotovoltaic Cell

Performance vs. Band Gap

Steven Wojtczuk

Notes:

$In_xGa_{1-x}As$ Thermophotovoltaic Cell Performance vs. Bandgap

Steven Wojtczuk, Edward Gagnon, Leo Geoffroy, and Themis Parodos
Spire Corporation
Bedford, MA 01730

Measured data will be presented on six compositions of indium gallium arsenide ($In_xGa_{1-x}As$) thermophotovoltaic (TPV) cells epitaxially grown, fabricated, and tested with bandgaps ranging from 0.74 eV to 0.5 eV. The goal was to study the tradeoff in electrical output power versus bandgap when the cells are illuminated with a 1000°C blackbody. The composition range begins with $In_{0.53}Ga_{0.47}As$, which has few defects since its crystal lattice is matched to the underlying indium phosphide substrate, but which has a high 0.74 eV bandgap (1.6 μm cutoff wavelength) not spectrally matched to the 1000°C blackbody (peak at 2.3 μm). The range ends with 0.5 eV $In_{0.8}Ga_{0.2}As$ that is spectrally close (2.6 μm) to optimum for the blackbody, but has substantial dislocation defects naturally generated to relieve the stress caused by the $In_{0.8}Ga_{0.2}As$ lattice differing from the InP wafer.

Figure 1 shows illuminated cell I-Vs under a weak (small area) calibrated 1000°C blackbody. The 0.64 eV bandgap ($In_{0.62}Ga_{0.38}As$) cells had the highest power output. Lower bandgap cells had more photocurrent, but less power output due to low voltages, caused both by the low bandgap and dislocations. Higher bandgap cells had more voltage, but less current due to long-wavelength radiation not being converted by the higher bandgap into electrical power. This work was funded by DOE grant (DE-FG02-93ER81619).

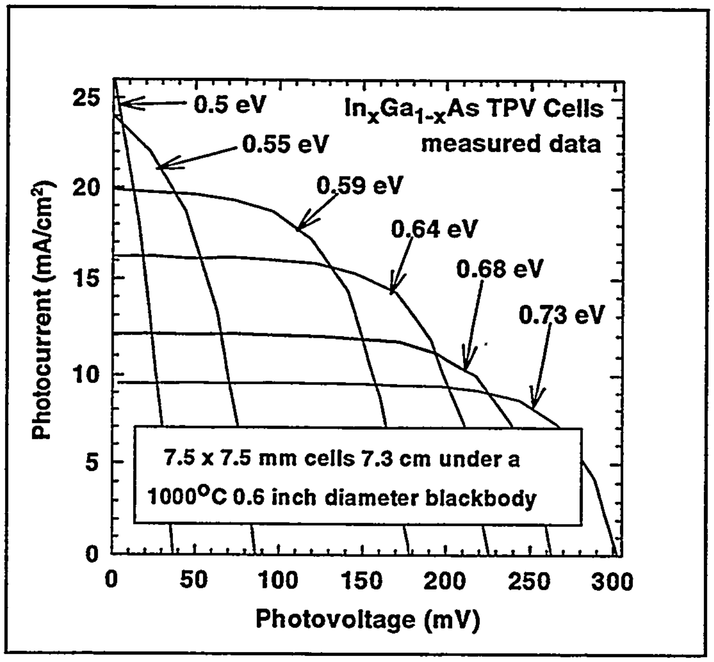


Figure 1 *Illuminated I-V curves of six $In_xGa_{1-x}As$ cells under a weak 1000°C blackbody.*

Notes:

Tuesday, July 26, 1994
8:45am - 9:00am

OMVPE Growth and Characterization of InGaAs for TPV Cells

Ishawara Bhat

Notes:

OMVPE Growth and Characterization of InGaAs for TPV Cells

H. Ehsani*, I. Bhat*, D. Marcy*, G. Nichols**,
J. Borrego*, J. Parrington**, and R. Gutmann*

*Center for Integrated Electronics and
Department of Electrical, Computer and Systems Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180

**Knolls Atomic Power Laboratory
Martin-Marietta Corporation
Schenectady, NY 12301

InGaAs lattice matched to InP has been studied extensively since its bandgap is ideally suited for the fabrication of detectors for application in fiber optical communications. For thermophotovoltaic applications in the 2.0 μm range, the ideal material is $In_{0.69}Ga_{0.31}As$. Unfortunately, lattice matched substrates are not available to grow this material in epitaxial form. One possible solution will be the use of InP substrate followed by a gradual variation of the lattice constant from that of $In_{0.47}Ga_{0.53}As$ lattice matched to InP to $In_{0.69}Ga_{0.31}As$ suitable for TPV cells. In this paper, we will report on the growth of lattice matched and lattice mismatched InGaAs layers on InP and the characterization of our results to date. The effect of different growth conditions and different buffer layers on the final layer properties will be described.

InGaAs growth was carried out by the organometallic vapor phase epitaxial process using trimethylgallium, trimethylindium and arsine. Both semi-insulating InP and p-type InP substrates were used. First, we carried out lattice matched undoped InGaAs layers on InP substrates. Hall effect and lifetime measurements have shown that the materials are of high quality. For example, Hall measurements show that the electron mobility for a layer with 1.5E16 cm^{-3} doping is 5500 cm^2/Vs at room temperature, and 16000 cm^2/Vs at 80K. The lifetime of minority carriers was measured using microwave reflectance technique. For an unpassivated 2 μm thick InGaAs layer, the lifetime was measured to be approximately 100 nS. Experiments are underway to grow $In_{0.69}Ga_{0.31}As$ layers using graded buffer layers. Detailed growth conditions and the layer properties will be reported at the conference.

Notes:

Tuesday, July 26, 1994
9:00am - 9:15am

Thermal Photovoltaic Cells

Michael Timmons

Notes:

Thermal Photovoltaic Cells

M.L. Timmons, P.R. Sharps, R. Venkatasubramanian
Research Triangle Institute
Research Triangle Park, NC 27709-2194

P.A. Iles and C.L. Chu
Applied Solar Energy Corp.
City of Industry, CA 91749-1212

The Research Triangle Institute (RTI) has recently begun developing low-band-gap materials that are suitable for energy conversion in the long wavelength regime of thermal energy, a regime that extends from about 1 µm to 5µm. Devices currently being fabricated are made of GaInAs alloys that have nominal band gaps of 0.6 eV. Devices made from materials with this band gap match thermal sources with peak blackbody emission wavelengths near 2 µm or selective emitters that operate in the same range.

In this paper we will describe the design considerations for these devices. Design considerations for devices made from other materials, including a quatarnary GaInAsSb, will also be presented. The advantages of more exotic materials such as the quaternaries will be pointed out. Attempts will also be made to point out shortcomings and tradeoffs of the current structures. Difficulties with metrology of the devices will also be outlined.

After presenting relevant design criteria, experimental results will be discussed. The experimental data that have been generated include I-V characterizations, spectral-response curves, and materials characterizations. An example of an I-V curve from one of the InGaAs devices is shown in Figure 1 below. Growth and fabrication details will be presented.

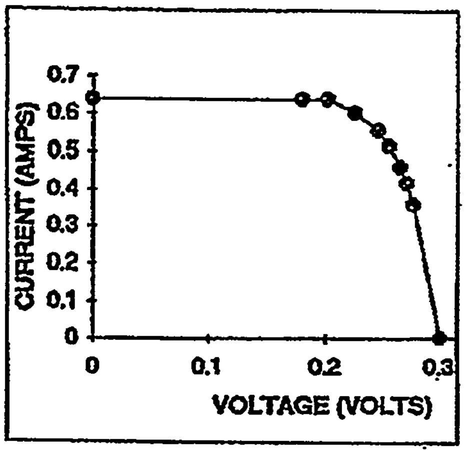


Figure 1. Illuminated I-V curve of 0.6-eV GaInAs TPV device. Cell parameters are the following:

V_{OC} = 0.3004 V
I_{SC} = 0.6388 A
FF = 0.711.

Cell measured under pulsed AMO solar simulator at 28°C.

Notes:

Tuesday, July 26, 1994
9:15am - 9:30am

Low Band Gap Solar Cells for Thermophotovoltaic Applications

Raj Jain

Notes:

Low Bandgap Solar Cells for Thermophotovoltaic Applications

R. K. Jain*, D. M. Wilt, G. A. Landis[+], I. Weinberg and D. J. Flood

Photovoltaic Branch (MS 302-1)
NASA Lewis Research Center
Cleveland, OH 44135

Photovoltaic solar cells can be used effectively and efficiently for non-solar applications. Thermophotovoltaic (TPV) power generation could reap the benefits of the tailored solar cells made of single, compound, ternary, and quarternary semiconductors. Today's advanced growth techniques allow bandgap engineering of materials suitably matched to the emission spectra of the radiation source.

This work will discuss the suitability of germanium (Ge), gallium antimonide (GaSb), and gallium indium arsenide (GaInAs) solar cells for TPV applications. Performance parameters of the record efficiency GaInAs cell developed at NASA Lewis Research Center along with other state-of-the-art solar cells developed have been considered. Calculations have been made for narrow (selective emitter) and broad band (blackbody) emission spectrum of the source. Our calculations demonstrate that the TPV solar cells exhibit high efficiencies. In TPV applications, the radiation source operates at high temperatures and intensities and it will be highly essential to keep solar cells cool. The effect of temperature on the solar cell efficiency/power output will be discussed. The increase in temperature also has a bandgap narrowing effect, which will reduce the cell voltage.

We have initiated modeling of low bandgap cells, and preliminary results will be presented. It is possible to develop ternary and quarternary compounds to select an optimum bandgap to suitably match the source spectrum. In most of the cases the source emission is at long wavelengths, it will be required to suitably change the solar cell design and processing (junction depths, dopings) to absorb the radiation efficiently to arrive at an optimized TPV cell design.

*supported by a NASA Grant at the University of Toledo
[+]NYMA Inc.

Notes:

Tuesday, July 26, 1994
9:30am - 9:45am

InGaAs PV Device Development for TPV Power Systems

David Wilt

Notes:

InGaAs PV Device Development for TPV Power Systems

David M. Wilt, Navid S. Fatemi [a], Richard W. Hoffman, Jr. [b], Philip P. Jenkins [a], David J. Brinker, David Scheiman [a], Roland Lowe [c] and Donald Chubb

Photovoltaic Branch, NASA Lewis Research Center, Cleveland, Ohio 44135

Thermophotovoltaic (TPV) power systems hold tremendous potential for providing power utilizing a variety of heat sources. To realize the high system conversion efficiency projected for TPV, photovoltaic devices with a range of bandgaps must be developed, with the operating temperature of the emission source dictating the bandgap required. We have been developing $In_xGa_{1-x}As$ photovoltaic devices with bandgaps from 0.55 eV to 0.75 eV for use with radioisotope and combustion heat sources. $In_xGa_{1-x}As$ devices, lattice matched to InP (Eg = 0.75 eV), have demonstrated AM0 efficiencies up to 11.2%. Lattice mismatched devices have been produced which incorporate $In_xGa_{1-x}As$ step graded buffer layers and pseudomorphic InP window layers. Devices with bandgaps of 0.60 and 0.66 eV have demonstrated AM0 efficiencies of 4.5% and 5.0 % respectively. Device performance under blackbody and selective emitter illumination, as well as device improvements will be discussed.

[a] Sverdrup Technology, Brookpark, Ohio 44121

[b] Analex Corporation, Brookpark, Ohio 44121

[c] Cleveland State University, Cleveland, Ohio 44115

Submitted to First NREL TPV Conference

Notes:

Tuesday, July 26, 1994
9:45am - 10:00am

Late News

Notes:

Tuesday, July 26, 1994
10:30am - 12:00pm

Session V

Selective Emitter Theory and Practice

Session Chairman

Kevin Krist

Notes:

Tuesday, July 26, 1994
10:30am - 10:45am

Emittance Theory for Thin Film Selective Emitters

Donald Chubb

Notes:

Abstract for First NREL Conference on Thermophotovoltaic Generation of Electricity
Emittance Theory for Thin Film Selective Emitter

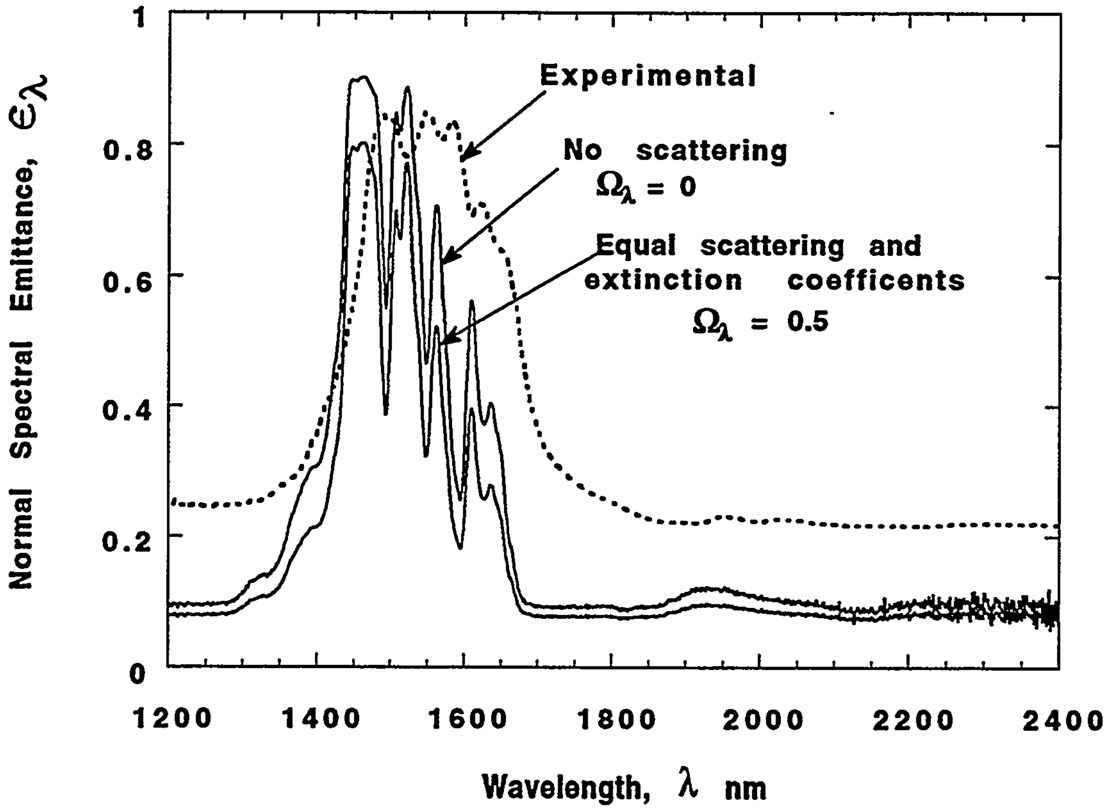
Donald L. Chubb, Roland A. Lowe & Brian S. Good
NASA Lewis Research Center, Cleveland, Ohio

An efficient selective emitter would make efficient theromphotovoltaic (TPV) energy conversion possible. In order to calculate the emitter efficiency, the emitter spectral emittance, ϵ_λ, must be known. This paper will present the radiation transfer theory used to calculate ϵ_λ. Also, emitter efficiency, η_E = power in emission band/total emitted power, will be presented.

The spectral emittance is obtained from the solution of the integral equation for the so-called radiation source function, S_λ. The source function depends on the optical depth, K_λ, $= \alpha_\lambda d$, ($\alpha_\lambda = \sigma_\lambda + a_\lambda$ is the extinction coefficient, σ_λ is the scattering coefficient, a_λ is the absorption coefficient and d is the emitter thickness), the scattering albedo, $\Omega_\lambda = \sigma_\lambda/\alpha_\lambda$, film index of refraction, n_f, and emittance of the substrate, $\epsilon_{\lambda s}$. An approximate solution for S_λ is obtained by using an exponential approximation for the exponential integral function and thus converting the integral equation to a solvable second order linear differential equation. Once S_λ is obtained, the spectral emittance, ϵ_λ, can be calculated.

Spectral emittance and efficiency results for the rare earth-garnet selective emitter developed at the Lewis Research Center will be presented. Comparison of theoretical and experimental ϵ_λ for the erbium-YAG (yttrium aluminum garnet) emitter are shown on the attached figure.

Notes:



Theoretical and measured spectral emittance of 40 % Er-YAG (1.04 mm thick) with a platinum foil substrate (emittance=.2) and index of refraction for YAG (n=1.9) at 1500 K

Notes:

Tuesday, July 26, 1994
10:45am - 11:00am

Composite Emitters for TPV Systems

P. Adair

Notes:

COMPOSITE EMITTERS FOR TPV SYSTEMS

P. Adair and M. F. Rose
Space Power Institute
231 Leach Science Center
Auburn University, AL 36849
Phone: 205-844-5923
Fax: 205-844-5900

Abstract

One important aspect of thermophotovoltaic (TPV) power systems is the need for an emitter which can produce radiation whereby electricity can be generated from photovoltaic cells. We have developed two types of emitter configurations which can be thermally excited by a heat source. These two configurations allow the emitter to produce the requisite emissions for matching to photovoltaic cells. The first emitter type, the selective line emitter, is made from oxides of the rare earth metals such as holmia. These emitters are made through a specialized series of processes which begin with nitrates of the rare earth metal and end with rare earth oxide filaments. These emitters produce a line output whereby a photovoltaic cell can be used which has a bandgap centered at this selective line. The second approach considered in our laboratory is to produce "modified" blackbody emitters which can withstand sufficiently high temperature operation and produce a significant amount of radiant energy. This requires the development of tandem cells which can utilize a larger portion of the emission spectrum. For both of these emitter types, conventional paper making techniques have been used to combine materials suitable as binders with the radiating material. As a result, this technique allows for fabrication of large area robust emitters which were heretofore unobtainable. Robust emitters made from holmium oxide have exhibited line emission with peak to background ratios of 6 to 1. This radiator will be described in some detail as representative of the process and will be used to illustrate the manufacturing technology developed at Auburn University. In this paper, we will describe the techniques for manufacturing both types of emitters, characterize the spectral characteristics, and discuss preliminary designs which would have sufficient area and robustness for various applications.

Notes:

Tuesday, July 26, 1994
11:00am - 11:15am

Temperature-Dependent Efficiency Calculations for a Thin-Film Selective Emitter

Brian Good

Notes:

Temperature-Dependent Efficiency Calculations for a Thin-Film Selective Emitter

Brian S. Good, Donald L. Chubb and Roland A. Lowe
NASA Lewis Research Center
Cleveland, OH 44135

Given the degree of current interest in thin-film thermophotovoltaic (TPV) devices, a realistic detailed estimate of the efficiency of these devices is of great importance.

In this paper we describe computer calculations of the efficiency of a rare-earth garnet selective emitter, based on the theoretical development of Chubb et al., who describe emitter efficiencies calculated assuming a constant temperature profile across the emitter thickness. It is known from experiment, however, that in many cases of interest the temperature is not constant. We have therefore extended this earlier work by computing numerically the emitter efficiency when the temperature is not uniform across the emitter thickness.

We have restricted our attention primarily to temperature profiles that are linear across the emitter thickness. This assumption is based on earlier simplified iterative computations of the temperature profile using a simplified source term, though these results are suggestive rather than definitive. In addition, we consider some limiting case profiles, thus obtaining bounds on the emitter efficiency.

Computed results will be presented for a variety of temperature profiles, as functions of scattering albedo, film index of refraction, and substrate emittance.

Notes:

Tuesday, July 26, 1994
11:15am - 11:30am

Some Characteristics of a Novel Direct Thermal to Optical Energy Converter Medium

Joseph Milstein

Notes:

Some Characteristics of a Novel Direct Thermal to Optical Energy Converter Medium

Joseph B. Milstein,* Ronald G. Roy,# and David C. Maurer*
* Department of Electrical Engineering
University of Massachusetts Lowell, Lowell, MA 01854
and
New Material Concepts, Inc.
15 Guile Avenue, Tewksbury, MA 01876

We have measured some of the optical characteristics of a novel energy conversion medium, over a range of compositions, which we have fabricated by a proprietary process. These specimens have good resistance to thermal shock, are durable, and are mechanically and chemically stable.

We examined compositions in the system Yb2O3-Al2O3. The specimens which we report here varied in pore size from 100 to 200 microns, and in composition from 75% Yb2O3 - 25% Al2O3 to 90% Yb2O3 - 10% Al2O3.

We have measured the integrated emission of light generated by these specimens when heated with a propane-air flame and detected with a silicon photodetector. The optical emission for these unoptimized specimens ranged up to 1.88 watts/cm2. Given the short duration of this effort, this compares quite favorably with fibrous emitters of mature technology which emit about 3 watts/cm2. We have determined the emission spectrum of these materials over the range of 0.8 microns to 1.8 microns using a germanium photodetector. We find a narrow emission band in the vicinity of 1 micron.

Our optical data clearly shows predictable variation of intensity of emission with changes in composition, pore size, and surface structure. We believe that significant further improvements in emission intensity and efficiency are yet to be made by optimizing each of these three variables. With such improvements, we expect that our material will produce competitive commercial products.

We are grateful for support for this work under DOE SBIR Phase I Grant DE-FG02-93ER81615.A000. We appreciate the use of equipment made available to us by Dr. R. Nelson of Tecogen, Mr. R. Ward of Germanium Power Devices Corporation, and Mr. J. Potter of Barr Associates.

Notes:

Tuesday, July 26, 1994
11:30am - 11:45am

Radiative Performance of Er and Ho-YAG Selective Emitters

Roland Lowe

Notes:

Radiative performance of Er and Ho-YAG Selective Emitters

Roland A. Lowe
School of Technology, Kent State University, Kent, Ohio 44242

Donald L. Chubb, Serene C.. Farmer, and Brian S. Good
NASA Lewis Research Center, Cleveland, Ohio, 44135

Thin film Ho-YAG and Er-YAG emitters with a platinum substrate exhibit high spectral emittance in the emission band ($\varepsilon_\lambda \approx 0.75$, $^4I_{15/2}$ - $^4I_{13/2}$, for Er -YAG and $\varepsilon_\lambda \approx$ 0.65, $^5I_7$ - $^5I_8$ for Ho-YAG) at 1500K. In addition, low out-of-band spectral emittance, $\varepsilon_\lambda < 0.2$, suggest these materials would be excellent candidates for high efficiency selective emitters in thermophotovoltaic (TPV) systems operating at moderate temperatures (1200-1500K). Spectral emittance measurements of the thin films were made ($1.2<\lambda<3.0\mu m$) and compared to the theoretical emittances calculated using measured values of the spectral extinction coefficient. Radiation efficiency (power in the emission band/total radiated power) is measured for the Er ($1.45<\lambda<1.70\mu m$) and Ho-YAG ($1.85<\lambda<2.25\mu m$) emitters.

Notes:

Tuesday, July 26, 1994
1:30pm - 3:00pm

Session VI

Programmatic and Systems Issues

Session Chairman

Anthony Catalano

Notes:

Tuesday, July 26, 1994
1:30pm - 1:45pm

An ARPA Perspective on TPV

Robert Rosenfeld

Notes:

Summary of Presentation

The Advanced Research Projects Agency (ARPA) has funded Quantum Group, Inc. in an 18 month project to demonstrate an efficient 10 kW thermophotovoltaic (TPV) power generator. The goal is to demonstrate a fuel-flexible, efficient, compact, and quiet power system. The project will also investigate applications of TPV to unmanned undersea vehicles.

Quantum Group has made good progress toward the goal. They will discuss that progress in a separate paper.

ARPA has also hosted a small workshop on TPV and discussed the technology with industry and Government leaders. All feel that TPV is a promising technology. ARPA has not budgeted funds for FY95 for continued TPV research. However, ARPA continues to maintain an interest in TPV and expects that success in Quantum's current effort and other TPV research will show that TPV can fulfill its promise.

Robert L. Rosenfeld, ARPA

Notes:

Tuesday, July 26, 1994
1:45pm - 2:00pm

The Role of DOE's Division of Advanced Energy Projects in Thermophotovoltaics

Cynthia Carter

Notes:

The Role of the DOE's Division of Advanced Energy Projects in Thermophotovoltaics

Cynthia Carter
Division of Advanced Energy Projects, ER-16
Basic Energy Sciences, Office of Energy Research
U.S. Department of Energy
Washington, D.C. 20585

ABSTRACT

The Division of Advanced Energy Projects (AEP) provides support to explore the feasibility of novel, energy-related concepts that evolve from advances in basic research. These concepts are typically in an early stage of definition and, therefore, are beyond the scope of ongoing applied research or technology development programs. The AEP also supports research on high-risk, exploratory concepts that do not readily fit into a program area but could have applications that may span scientific disciplines or technical areas.

Materials research for components required for thermophotovoltaics may have developed to the stage that TPV is a candidate energy conversion area for exploration and evaluation via AEP support. If it could now be made into a competitive alternative for electricity generation, the pay-off could be enormous. Research projects that explore this question from different perspectives are being considered for addition to the AEP portfolio.

This presentation will describe the rather unique AEP program charter as a seeding funding source to explore uses of basic research results to fulfill the DOE's mission.

Notes:

Tuesday, July 26, 1994
2:00pm - 2:15pm

TPV Power Source Development for an Unmanned Underwater Vehicle

Glenn Holmquist

Notes:

TPV Power Source Development for an Unmanned Underwater Vehicle

Glenn A. Holmquist, Quantum Group, Inc., San Diego, CA

ABSTRACT

The thermophotovoltaic generation of electrical power promises efficiencies that are exploitable for military and commercial applications. Recent accomplishments have resulted in increased government interest. TPV offers a combination of unique characteristics as a power source for military Unmanned Underwater Vehicles. In civilian applications TPV technology offers the potential for lightweight, rugged, and reliable power systems that can be environmentally benign. These systems can use a variety of fuels and can be scaled up in size. TPV is truly a dual use technology in which the United States has a technical lead. The focus of the DoD ARPA program is the maturation of the technology and the demonstration of a 10 kilowatt generator. Preliminary results from the first 9 months of this 18 month project are presented.

Notes:

Tuesday, July 26, 1994
2:15pm - 2:30pm

Systems and Marketing Challenges for TPV

Eugene Ralph

Notes:

SYSTEMS/MARKETING CHALLENGES FOR TPV

E.L. Ralph, M. FitzGerald
APPLIED SOLAR ENERGY CORPORATION

ABSTRACT

Thermophotovoltaic technology has been considered as an electrical power source for many years. The principles have been well documented and demonstration units have shown the feasibility of these TPV systems. One of the major challenges, however, has been the marketing of TPV systems even though a large number of potential applications have been identified. This paper will discuss why this has happened in the past, and why we are now at a point where the market opportunities will open up in the future.

The primary driver for TPV in the past has been a very specialized need for military field generators for special forces, and as a man-pack battery re-charger. Because of this limited application, most of the emphasis was on research and little was done to commercialize the systems. Now the situation has changed, and there is a strong tendency to look for new ways to commercialize military systems. This paper will describe some of the emerging TPV markets that are developing both for the government and for commercial applications and how the eventual system design(s) must take these market requirements into consideration.

Some of the reasons that new applications are looking more interesting, as well as some indications of what performance and economical goals must be met to satisfy these applications will be discussed in the paper. Various applications such as gas furnace heater electrical power, quiet motor generators for recreational vehicles, underwater vehicle power, radioisotope spacecraft power, and automotive (green car) electrical generators will be evaluated and discussed as potential new market areas.

Notes:

Tuesday, July 26, 1994
2:30pm - 2:45pm

TPV Conversion of Nuclear Energy for Space Applications

Jose Martin

Notes:

TPV CONVERSION OF NUCLEAR ENERGY FOR SPACE APPLICATIONS

Thomas M. Regan and José G. Martín
Department of Chemical and Nuclear Engineering, University of Massachusetts Lowell
Juanita Riccobono
Northeast Photosciences

When TPV is part of an open-loop combustion-powered system, a large amount of thermal is discharged even when recuperators are used. This paper explores the possibility of achieving high conversion efficiencies in a closed system by replacing the combustion heat source with a nuclear thermal source such as a high-temperature gas cooled reactor. Possible applications are nuclear electric propulsion and power for mission support systems in space.

HTGR's use helium or a helium blend for the working fluid. The outlet temperature is limited by pump material technology, but it can be high - in a Pebble Bed Reactor, helium may leave the reactor at 1800K and 2MPa. Although a major design goal for a HTGR-powered TPV converter is to transfer as much of this energy as possible to a selective emitter, the left-over high enthalpy gas may be recirculated.

Although the system could use fiber matrix[1] or line emitter[2] geometries, the work reported here concentrates on using spectrally selective coatings on the outside surfaces of pipes constructed of low-emittance refractory materials. Specifically, we are considering rare earth oxide coatings such ad neodymium or holmium oxide deposited on aluminum oxide or beryllium oxide.
Possible pv cells are germanium (for the neodynium oxide) and GaSb (for the holmium oxide).

The cells must be kept cool, and to do this one must ensure that as much of the light energy reaching the cells is converted to electricity as possible. A major innovation in the proposed nuclear-TPV system is the use of holographic optical elements, similar to those which have been tested here for solar space conversion [3] These elements act as off-band filters: they enhance the effect of the selective emitter, to ensure that only "usable" photons reach the cell.

This helps keep the cells cool - and allows the introduction of another possible design feature. The holograms can act as concentrators for the "narrow band" emission, allowing a reduction of the pv area. Holograms can be integrated into an optical configuration with elliptical cross-section, where one of the foci is occupied by a tubular thermal source. The holograms redirect the light toward the (band-dependent) other focus, in such a way that they are intercepted by the converters.

A small open-loop model has been built to demonstrate the concept that an emitter can be thermally excited by helium. An electric thermal source heats Helium to about 1000K in a nichromic alloy tubing. This section is connected to a Lucalox tubing housing a holmium oxide emitter. Measurements are being made on the spectral emission.

Studies are also underway, aimed at scoping the power densities achievable in the converter for a 250Kwe source. Assuming fluxes of the order of 2 watts/cm2 from the emitter, and an elliptical optical configuration measuring 12cmx8cm, with tubes of surface area of 3.414 cm2/cm, it seems that a nuclear-power TPPV generator could produce 100 Kw. per cubic meter of converter.

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[1] Nelson, R. P. Thermophotovoltaic Technology, U.S. Patent No. 4,826,426, May 2, 1989

[2] A. Schock, M. Mukunda, T. Or, V. Kumar, and G. Summers, "Radioisotope TPV Generator...", FSC-ESD-217-93-519A

[3] J. E. Ludman, J. L. Sampson, R. A. Bradbury, J. G. Martin, J. R. Riccobono, G. Sliker, E. Rallis, "Photovoltaic systems based on spectrally selective holographic concentrators", Practical Holography VI, SPIE Vol. 1667, p. 182(1992).

Notes:

Tuesday, July 26, 1994
2:45pm - 3:00pm

Analysis Optimization, and Assessment of Radioisotope Thermophotovoltaic System Design for an Illustrative Space Mission

A. Schock

Notes:

ANALYSIS, OPTIMIZATION, AND ASSESSMENT OF RADIOISOTOPE THERMOPHOTOVOLTAIC SYSTEM DESIGN FOR AN ILLUSTRATIVE SPACE MISSION

A. Schock, M. Mukunda, T. Or, and G. Summers
Fairchild Space and Defense Corporation
Germantown, MD 20874 U.S.A.
(301) 428-6272

Abstract

A companion paper presented at this conference described the design of a Radioisotope Thermophotovoltaic (RTPV) Generator for an illustrative space mission (Pluto Fast Flyby). It presented a detailed design of an integrated system consisting of a radioisotope heat source, a thermophotovoltaic converter, and an optimized heat rejection system. The present paper describes the thermal, electrical, and structural analyses which led to that optimized design, and compares the computed RTPV performance to that of a Radioisotope Thermoelectric Generator (RTG) designed for the same mission.

RTPVs are of course much less mature than RTGs, but our results indicate that - when fully developed - they could result in a 60% reduction of the heat source's mass, cost, and fuel loading, a 50% reduction of generator mass, a tripling of the power system's specific power, and a quadrupling of its efficiency.

The paper concludes by briefly summarizing the RTPV's current technology status and assessing its potential applicability for the PFF mission. For other power systems (e.g. RTGs), demonstrating their flight readiness for a long-term mission is a very time-consuming process to determine the long-term effect of temperature-induced degradation process. But for the case of the described RTPV design, the paper lists a number of factors, primarily its cold (0 to 10°C) converter temperature, that may greatly reduce the need for long-term tests to demonstrate generator lifetime. In any event, our analytical results suggest that the RTPV generator, when developed by DOE and/or NASA, would be quite valuable not only for the Pluto mission but also for other future missions requiring small, long-lived, low-mass generators.

Notes:

Wednesday, July 27, 1994
8:15am - 10:00am

Session VII

Device Fundamentals

Session Chairman

David Ginley

Notes:

Wednesday, July 27, 1994
8:15am - 8:30am

Parameter Extraction for TPV Cell Development

Jose Borrego

Notes:

Parameter Extraction for TPV Cell Development

J. Borrego*, M. Zierak*, and G. Charache**

*Center for Integrated Electronics and
Department of Electrical, Computer and Systems Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180

**Knolls Atomic Power Laboratory
Martin-Marietta Corporation
Schenectady, NY 12301

During the development of TPV cells it is desirable to be able to extract the important material and device structure parameters of cells. The two most important parameters of the cells impacting device performance are the bulk lifetime and the interface or surface recombination velocity. In this paper, we present the modeling that has been developed using PC-1D for InGaAs TPV cells for extracting information of bulk lifetime and interface recombination velocity from external quantum efficiency and surface reflectance measurements. In addition, measurement of the doping concentration and of the depletion layer at zero bias from capacitance measurements allows us to match the internal quantum efficiency of the TPV cells with only two parameters: excess carrier lifetime and interface or surface recombination velocity. In the paper, we will give examples of parameters obtained in GaInAs TPV cells, and compare them with measurements of the lifetime of GaInAs layers using microwave reflection.

Notes:

Wednesday, July 27, 1994
8:30am - 8:45am

The Design and Modeling of Photovoltaic Cells for TPV Systems

Richard Schwartz

Notes:

The Design and Modeling of Photovoltaic Cells for TPV Systems

Richard J. Schwartz and Jeffrey L. Gray

School of Electrical Engineering
Purdue University
West Lafayette, In 47907
317 494 3539
317 494 6440 (FAX)

There are a number of issues which arise in the modeling and design of photovoltaic cells for use in thermophotovoltaic systems which make the design of these cells significantly different from those of one sun terrestrial or space cells. Some of the issues are the same as those which must be addressed in high concentration applications and in fact some of the early TPV cell designs were used in high concentration cells.

The issues which are addressed in this paper are:

1. High intensity effects. TPV systems will typically operate in the 10 w/cm^2 region. These high concentrations can effect the physics of operation as well as design considerations.
2. The effects of light trapping on the performance of the cell in the presence of a broad band/narrow band emitters.
3. The effects of free carrier absorption and how this may depend on the illumination intensity.
4. Effects of carrier-carrier scattering at high illumination intensities.
5. The need for and effects of Fermi Dirac statistics.
6. The effects of absorption edge temperature shifts on the operation of cells designed to operate with selective emitters.
7. The effect of the requirement for a large acceptance angle inherent in most TPV systems.

Examples will be drawn primarily from our experience with the modeling and fabrication of silicon cells but will include a few examples from our experience with narrower gap materials (germanium and some of the compound semiconductors). The tradeoff between cells designed for operation with selective emitters and cells designed for use with gray body emitters will be discussed. Comparisons between cells with front surface and back surface reflectors will be presented. Realistic estimates of potential cell operating efficiencies will be presented.

Notes:

Wednesday, July 27, 1994
8:45am - 9:00am

Proposal for a Second-Generation, Lattice-Matched, Multiple-Junction Ga_2AsSb TPV Converter

Greg Horner

Notes:

Proposal for a Second Generation Lattice-Matched, Multiple Junction Ga_2AsSb TPV Converter

G.S. Horner, T.J. Coutts and M.W. Wanlass
National Renewable Energy Laboratory, Golden, CO, 80401

The device structure proposed here utilizes the phenomenon of spontaneous ordering for band gap control. Ordering in III-V semiconductors has received much attention since its discovery in 1986, both as a matter of basic scientific exploration, as well as for possible device applications. Devices that utilize the reduced band gap of CuPt ordered material have seen applications in both high-efficiency solar cells and far infrared detectors. The material Ga_2AsSb has been shown to exhibit CuPt ordering, but no device applications have been realized. The device modeling presented here demonstrates that ordered Ga_2AsSb is an ideal candidate for high-efficiency, multiple junction TPV applications.

The material Ga_2AsSb is lattice matched to readily available InP substrates, and nominally exhibits a (disordered) room temperature band gap of ≈0.84 eV. Theoretical predictions by S.-H. Wei and Alex Zunger [N.R.E.L.] place the 'perfectly ordered' band gap near ≈0.33 eV (corrected to room temperature). Although perfectly ordered material has never been grown, a range from ≈0% to ≈75%-ordered material is typically accessed for the most studied system, $GaInP_2$. The degree of ordering leaves the average atomic composition, and hence the average lattice constant, unchanged. Thus, Ga_2AsSb should remain lattice matched to InP as the band gap is varied between 0.84 and 0.5 eV due to changes only in the microscopic ordering. This feature overcomes the typical dark current problems associated with lattice-mismatched growth in the ternary systems.

In this paper, a series of modeling calculations will be presented which predict efficiency (30% for a 1400 K emitter), open circuit voltage, fill factor and short circuit current over a range of emitter temperatures. The flexibility afforded by the continuously variable band gap allows the designer to 'tune' a *lattice-* and *current-*matched device to the emission spectra emanating from 1000-2000 K blackbody radiators.

Notes:

Wednesday, July 27, 1994
9:00am - 9:15am

High Performance Contacts to GaInAs TPV Converters

Scott Ward

Notes:

High Performance Contacts to GaInAs TPV Converters

J.S. Ward, X. Wu, M.W. Wanlass, and T.J. Coutts
National Renewable Energy Laboratory
Golden, CO, USA.

Thermal photovoltaic converters present an interesting challenge to contact designers. As is the case for terrestrial concentrator devices, TPV converter metallization must be capable of sustaining operation at very high current densities without significant resistive losses. However, unlike concentrator systems where the illuminated area is small in comparison to the size of the module, proposed TPV emitter systems radiate high power densities over relatively large areas. This makes issues like packing fraction and bus bar sizing, which are normally more relevant to flat plate technologies, critical to the overall efficiency of a TPV system.

This work represents our efforts to apply the lessons learned in terrestrial concentrator grid design and metallization to TPV converters based on APMOVPE grown GaInAs. We report on the modeled and measured performance of Ti/Pd/Ag contacts deposited by electron beam vacuum deposition. Adhesion, thermal stability and fabrication issues are also addressed.

Notes:

Wednesday, July 27, 1994
9:15am - 9:30am

Recombination Lifetime of $In_xGa_{1-x}As$ Ternary Alloys

Richard Ahrenkiel

(paper not available at time of print)

Notes:

Wednesday, July 27, 1994
9:30am - 10:00am

Part I:

Important Factors in Determining the Efficiency of TPV Systems

Part II:

A Detailed Analytical Model (with typical numerical results) for Evaluating Radiative Transfer Efficiency of a Finite Flat Plate TPV System

David White

(paper not available at time of print)

Notes:

Wednesday, July 27, 1994
1:30pm - 3:30pm

Session VIII

Device and Material Characterization

Session Chairman

Lawrence Kazmerski

Notes:

Wednesday, July 27, 1994
1:30pm - 1:45pm

Characterization of Thermophotovoltaic Cells

Robert Mueller

Notes:

Characterization of Thermophotovoltaic Cells

By Dale R. Burger and Robert L. Mueller
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT - Thermophotovoltaic (TPV) research has reached a period of rapid expansion after 30 years of effort yet there is still no comprehensive method of TPV cell characterization. To support this surge in research, the Jet Propulsion Laboratory has developed many necessary procedures for TPV cell characterization. This low-cost, pioneering effort was made possible by utilizing or modifying available equipment. Simple procedures allow the derivation of temperature coefficients for Voc and Isc, as well as the intensity coefficient for Voc. Specific standard spectra are used while both the source intensity and the cell temperature are adjusted. Measurements of cell external spectral response and dark forward and reverse diode current are used to further characterize the cell. Standard operating conditions of spectrum, intensity and cell temperature are proposed so that TPV cell performance and efficiency data will be universally accepted for cell comparison. Examples of TPV cell data are illustrated and a description of test apparatus is also presented. This cell characterization effort permits modelling the performance of a TPV cell in a total TPV system. In addition to system modelling, cell design and TPV cell material development efforts are also supported.

Notes:

Wednesday, July 27, 1994
1:45pm - 2:00pm

Characterization of GaInAs TPV Cells

Michael Zierak

Notes:

Characterization of GaInAs TPV Cells

M. Zierak*, J. Borrego*, J. Parrington**, G. Charache**, I. Bhat*,
H. Ehsani*, D. Marcy*, G. Nichols**, and R. Gutmann*

*Center for Integrated Electronics and
Department of Electrical, Computer and Systems Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180

**Knolls Atomic Power Laboratory
Martin-Marietta Corporation
Schenectady, NY 12301

In this paper we present the laboratory measurement techniques we have developed to characterize the performance of large area GaInAs TPV Cells. Characteristics we determine are: I-V characteristics under dark and illuminated conditions, lifetime of excess carriers using Open Circuit Voltage Decay, Doping Concentration, Contact Potential, External Quantum Efficiency and Surface Reflection. The determination of excess carrier lifetime using Open Circuit Voltage Decay uses a high frequency fixture which allows measurement of lifetime as short as a few nanoseconds. The I-V characteristics under dark and illuminated conditions are done on a pulsed basis to avoid the necessity of an elaborated heat sinking and allows the measurement of I-V characteristics at currents as large as 10 amps. In the presentation we will show results obtained on a variety of InGaAs cells tested for determining their optimum operating current density.

Notes:

Wednesday, July 27, 1994
2:00pm - 2:15pm

Performance Characterization of Thermophotovoltaic Cells

Keith Emery

Notes:

Abstract for First NREL Conference on Thermophotovoltaic generation of Electricity

Performance Characterization of Thermophotovoltaic Cells

Keith Emery
NREL

The performance of photovoltaic cells is often expressed in terms of the efficiency. Procedures for determining the efficiency for flat-plate and concentrator cells operating under natural sunlight have been established and standardized. These procedures rate the efficiency in terms of a reference temperature, reference total irradiance, reference spectral irradiance, and an area definition. Reference conditions have not been established for thermophotovoltaic devices resulting in large differences in the efficiency between groups and technologies. A strategy for determining a limited set of reference conditions for comparing TPV performance between various groups and technologies will be discussed.

This talk will address the merits and problems of the different methods for determining the TPV efficiency with respect to a given set of reference conditions. The problem reduces to determining the short-circuit current (I_{SC}) at a particular reference temperature, total and spectral irradiance and measuring the current *versus* voltage characteristics with the device producing that short-circuit current and computing the maximum TPV power. In some cases I_{SC} must first be translated to a particular reference temperature, total and spectral irradiance. For multiple reference conditions, the maximum TPV power may have to determined from a measurement of the power *versus* temperature and I_{SC} over the range of interest. If the absolute external spectral responsivity or quantum efficiency is known, then I_{SC} can be directly computed from integrating with the reference spectral irradiance and normalizing the data to the reference total irradiance. There are a variety of errors associated with absolute quantum efficiency measurements, so the extraterrestrial community determines the I_{SC} directly by exposing the sample to the reference spectral irradiance distribution (e.g.. balloon flown primary AM0 reference cell). The terrestrial community exposes a PV cell to natural sunlight and measures I_{SC} and total solar irradiance and applies a correction for the spectral error. If the I_{SC} of a TPV cell could be accurately determined by exposing the sample to a well defined total and spectral irradiance distribution such as an ideal black-body and the relative spectral response and temperature coefficient can be measured, then the I_{SC} for any given set of TPV reference conditions can be determined. It is possible to translate the I_{SC} of a TPV cell calibrated as a terrestrial or AM0 cell to a given set of TPV reference conditions but the error in the translation can be large depending on how accurately the relative spectral responsivities are known. A variety of procedures currently exist to accurately measure the performance of a TPV cell with respect to any given set of reference conditions. Uncertainty analyses of the various methods along with a cost analysis is required to determine the most cost effective and accurate method for a given group to employ in determining the TPV efficiency.