# COMPONENT DEVELOPMENT

## Thermophotovoltaic Research at Sandia National Laboratories

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Thermophotovoltaic (TPV) power systems have potential use in many power generating applications: waste heat recovery in high temperature industrial processes, lightweight miniature electrical power generators, and solar concentrators with sunlight converted infrared radiation by a high temperature emitter. Our focus at Sandia National Laboratories has been to develop TPV device fabrication and characterization capability for use in a variety of thermal energy to electrical power conversion applications. This research and development effort includes epitaxial growth of 0.6eV InGaAs / InP, die fabrication of novel flip-chip multi-junction monolithic interconnected module (MIM) devices, packaging of devices into power systems using high temperature materials, characterization of TPV devices and systems with a variety of infrared emitters, and modeling TPV device and system capability. Wavelength selective emitters and filters - such as photonic crystals, interference filters, and spectral control filters – boost TPV performance further. Our work and results will be presented with recent advances.

# TPV CELLS

## Cost-efficient thermophotovoltaic cells based on germanium substrates

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When thermophotovoltaic systems are compared to classical photovoltaic systems, two main aspects are distinctly important. First, due to the small distance between the receiver cells and heat source, a high photon flux will be incident on the cell. Secondly, due to the relatively low temperature of the heat source compared to the sun, the emitted photons will have a long wavelength. These two differences result in a need to apply optical confinement in the receiver cells, as well as an optimized front contact structure. In this paper, the results on the realization of optical confinement together with the application of local contacting on the rear with laser fired contacts (LFC) will be discussed.

The optimized processing of a low-cost germanium TPV cell will be discussed focusing on the optimization of the front contact, consisting of a stack of Pd/Ag, and highly reflective rear contact consisting of a stack of a-Si/SiO2/Al. The front contact formation will be studied in more detail by TEM analysis while the electrical quality of the front contact structure has been tested under concentrated illumination (AM1.5G X 1-30). We have shown that the realized front contact performs well up to concentration ratio's of 30 suns which proves that this type of contact is suitable for application in TPV systems. A germanium TPV cell having a highly reflective rear contact where contact is realized using LFC performs well at a concentration ratio ofAM1.5G x 6 suns giving an efficiency of 5.3%.

# Diffusion technology for high-performance InGaAs TPV cells.

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Characteristics of inverted InP/InGaAs thermophotovoltaic (TPV) cells with n-on-p polarity fabricated on electrically active n-type InP substrates are presented. Thermophotovoltaic cells based on lattice matched InP–$In_{0.53}Ga_{0.47}As$ heterostructures were fabricated with the use of LPE and P and Zn diffusion from local sources in an open system in the hydrogen atmosphere. A p-doped base is formed into a phosphorus doped InGaAs by Zn diffusion.

The influence of additional isovalent phosphorus doping on the material properties and the photovoltaic parameters of the devices was studied. Cells with isovalent doping show an increase of the minority carrier lifetime in the quasi-neutral n-emitter region, a decrease of the reverse saturation current density and an increase in the fill factor. TPV cell structures were optimized as a function of the doping concentration and thickness of the active regions.

Electrical measurements using a flash tester reveal the open circuit voltage of 0.45÷0.50V, the fill factor of 76÷78% at short circuit current density of 1÷20A/cm$^2$. The calculated efficiencies for a TPV cell are 16÷18% for the tungsten emitter and 10% for the black-body source at temperature of 1800÷2000K.

Thus, the developed technique of additional isovalent phosphorus doping and Zn diffusion from a local sources has a high potential as an efficient low cost method for manufacturing of TPV cells and can be successfully used in industrial production.

# The development and testing of inverted 0.6-eV InGaAs thermophotovoltaic monolithic interconnected modules on InP using strain-relaxed InPAs buffers.

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Thermophotovoltaic (TPV) energy conversion is being developed for cogeneration and remote power generation applications. A strain-relaxed InPAs buffer grown on a semi-insulating InP substrate serves as a template for unstrained 0.6-eV InGaAs TPV cell growth. We used monolithic interconnects for serial cell arrangements allowing voltage to accumulated above that achieved for a single junction device. Our design implements an inverted geometry to enable illumination through the InP substrate eliminated scattering of light from metal interconnects. Processed cells show open circuit voltages greater than 380 mV per junction and external quantum efficiencies of 90%. Fill factors over 70% were obtained. Linear voltage accumulation with the number of cells was observed. The details of growth, processing and testing will be discussed further.

# PHOTOVOLTAIC CONVERTER ARRAY

## Modeling of Low Bandgap Thermophotovoltaic Diodes for Design of Portable Power Systems

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Recently, we have seen tremendous advances in low bandgap cells and spectral control, yet little on their implications to system design. We focus on developing a detailed parametric circuit model for the most promising diode technologies. The model allows us to optimize our design of a portable thermophotovoltaic system for efficiency and power density. We fit the single diode model to three types of cells under different conditions and study how the five parameters (photocurrent, dark current, ideality, and series and shunt resistance) vary with temperature and illumination. To verify the model, we illuminated the cell with blackbody radiation and calculated the photocurrent from the quantum efficiency. The photocurrent and cell temperature served as the inputs to the model. At low illumination intensities the model's predictions match experimental data very well. For high intensities we modified the model to account for cell heating to achieve good agreement.

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# IR EMITTERS

## Numerical Simulation on EM Wave in Optical Fiber Probe for detecting Spectral-Controlled Evanescent Wave on Emitters

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Scattering of evanescent wave and propagation in an optical fiber probe were investigated through electromagnetic wave simulation in time domain for effective detection. In order to analyze thermal radiation as an electromagnetic wave, a dipole emission source was fixed at each grid point inside an emitter which was assumed to be a nickel metal. The direction of each dipole and the phase were given randomly, while the frequency was specified in each numerical analysis. In the case of wavelength longer than the fiber probe aperture, the radiation intensity introduced (scattered) into the fiber probe increased drastically with decreasing distance between the surface and the probe since the evanescent wave effect became remarkable. At the same time, a wave propagating into the outside of the probe was also confirmed as a scattering wave from the evanescent wave. Finally, spectral transmission characteristics of the probe were investigated.

# SPACE APPLICATION

## Emitter Evaporation Study in Space TPV Systems

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Some NASA space missions are not well suited for solar energy power generation and therefore must use an alternative power source. Thermophotovoltaic (TPV) systems use direct photovoltaic (PV) conversion of heat to electricity and the higher the source temperature, the more efficient they are. Most TPV systems use an emitter material between the heat source and the PV array to improve performance. With this being the case, condensation of evaporated emitter material onto the PV array cannot be tolerated because of extreme performance penalties. As a result, the Evaporation Rate Measurement System (ERMS) facility was constructed at the NASA Glenn Research Center to measure the evaporation rate of candidate emitter materials. This paper will describe the ERMS facility and how the evaporation rate and vapor pressure are determined. Two of the lowest vapor pressure metals, tungsten (W) and tantalum (Ta) were tested in this facility. Results for W at 1350° K front side temperature for 107 days will be presented. Ta testing has recently concluded in the facility with an excess of 118 days at 1350° K front side temperature. Preliminary results for the Ta emitter test will be presented.

# Emitter function and emittance measurement relevant to a 250 $W_t$ Class RTPV Generator for Space Exploration

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A description is given of a planned 250 $W_t$ Radioisotope Thermophotovoltaic (RTPV) power system for utilization in lunar exploration and subsequent exploration of Mars. Emitter selection criteria are given for use in a maintenance free power supply that is productive over a 14 year mission life. Thorough knowledge of a material's spectral emittance is essential for accurate modeling of radiant heat transfer. While sometimes treated as a surface effect, emittance involves radiation from within a material. This creates a complex thermal gradient which is a combination of conductive and radiative heat transfer mechanisms. Emittance data available in the literature is a useful resource but it is particular to the test sample's physical characteristics and the test environment. Analysis of making relevant spectral emittance measurements is presented. Measured spectral emittance data of refractory emitter materials is shown and a method to improve relevance to the current project is discussed.

# Developments in Radioisotope Thermophotovoltaic Power Systems

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Radioisotope thermophotovoltaic (RTPV) power systems have the potential for both high efficiency (>15% projected) and high mass specific power (8W/kg projected). Previous system development activities by the authors have demonstrated and estimated high converter efficiency with an estimated 80% of the initial power output remaining factor at the end of a 14-year mission life (radiation effects only). Recent research activities have focused on the design and fabrication of an improved test facility for accurate characterization of the energy balance during high temperature testing. Other activities have included the development of improved tandem filters, emitter development, and investigation of emitter degradation mechanisms.

# CHP APPLICATION

## Demonstration of a TPV integrated boiler concept

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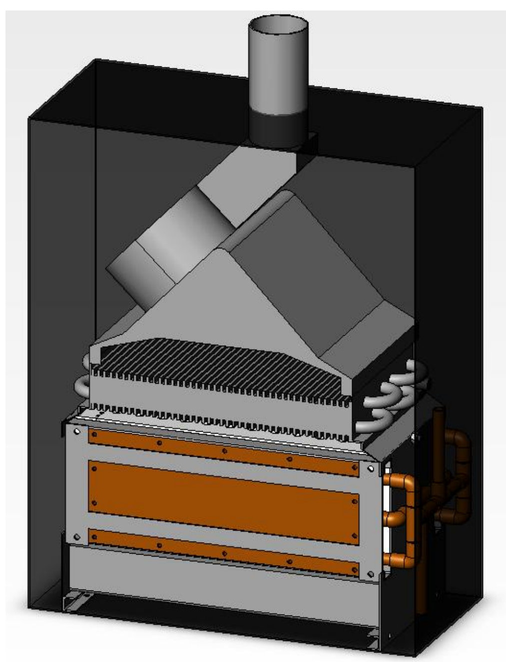
Interest has grown in direct thermal-to-electric energy conversion using solid state technologies such as thermophotovoltaics (TPV). TPV generation of electricity can be applied to self-powered heating appliances, micro-CHP and stand-alone power generators. TPV integrated fuel-fired heating equipment converts a portion of heat to electricity and operates without connection to electric utility. Thus, the values provided to the consumer would be both the heating system reliability and a reduction in home power consumption. In the present study, a natural gas-fired TPV setup using low bandgap GaSb cell modules has been researched, built and tested so as to evaluate various issues related to combustion-driven TPV power generation. Then a TPV integrated residential boiler has been devised and investigated, as illustrated below. A commercially available gas-fired boiler is used as a precursor to construct the TPV integrated system which provides a power generation capacity of 250 W. Development of self-powered heating equipment is considered as a first target, and some consideration is also being given to the technical feasibility of upgrading the equipment to a 1 kWe range micro-CHP system.



TPV self-powered residential boiler

# A Compact ThermoPhotoVoltaic (TPV) Generator Using Boiling Liquid Cell Cooling

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A design will be presented for a compact 48 W TPV generator with dimensions of 14 cm high, 18 cm wide, and 5 cm deep built around a simple Bunsen burner. Our TPV generator design contains a GaSb IR circuit using top and bottom symmetric rows of 12 cells each with 24 cells total. This circuit surrounds a SiC mantle emitter 3 cm in diameter and 3 cm tall glowing at 1450 C. Our calculations then suggest that this circuit will produce 48 W of electricity (approximately 7 V and 7 Amps). Imagine 1 $cm^2$ cells producing 2 W of electricity per $cm^2$. Calculations suggest that the heat load per cell might then be 15 W/cm2. With a boiling coolant, this heat could be transferred to 2 compact fan-cooled heat exchanger with 20 times more surface area to transfer this heat to the air. Given the 4.3% electrical conversion efficiency we calculate, a fuel burn rate of 1120 W would be required. A simple Bunsen burner can operate at a combustion rate of up to 3 kW, more than enough power than required as per our calculation. This would be an amazingly compact and powerful little TPV generator. The key to this compact size will be the demonstration of boiling liquid cooling for the GaSb cells.

# SOLAR APPLICATION

## Modelling Solar Thermophotovoltaic systems for loss analysis and efficiency prediction of real systems

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A model of a Solar Thermophotovoltaic (STPV) system based on an analytical ray tracing method is used for predicting the performance of a real STPV system, which has been developed and measured at our laboratory under outdoor conditions. From the measurements, an efficiency of around 4% (without considering the concentrator efficiency) has been obtained, which matches with the model prediction for such a configuration. Then, using the model, the contribution of each component to the losses of the full system has been calculated. Furthermore, it is also shown the effect over the whole system performance of modifying the properties of some components and also the geometric configuration of the system. In the paper we will demonstrate that an efficiency greater than 10% is practically achievable with some relatively simple changes in the system configuration. This efficiency is achievable by the use of some already available components (anti-reflecting coated cylindrical tungsten emitters and back-reflector germanium PV cells) that have been developed in the frame of the FULLSPECTRUM project. Efficiencies up to 14-16% could be obtained with such components but working with concentration factors greater than 5000 suns.

# Hybryd solar/fuel TPV generator

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A prototype of a TPV system with a mixed solar/fuel energy source is presented. The developed system utilizes a large 0.6x0.6 $m^2$ Frenel lens for the concentration of the solar energy. A propane camping gas was used as the fuel source. The emitters in the developed system are made of tungsten for the solar only operation regime and from the heat-resistant iron-based alloy for the mixed fuel-solar energy source. Tungsten emitter was coated by a 200 nm thick $HfO_2$ layer for better selectivity of the emission spectrum. The fuel-fired emitter has a netted structure for the gas flow and a quartz window for the sunlight input. The emitter temperatures were ~1550 $^0$C for the tungsten emitter at solar operation and ~1450 $^0$C for the mixed (solar/fuel) energy source. The solar energy in the mixed regime is used for the fuel saving.

An extensive study was performed on the TPV arrays. The modules consisting of three 1x1 $cm^2$ GaSb cells have been developed, for a TPV generator operating with a cylindrical emitter 25 mm long. The fill factor of the array consisting of three 1x1 $cm^2$ GaSb cells at the current density of about 1.8 $A/cm^2$ have the maximum value of 67 % and output power of such array was about 1.5 W measured at pulsed illumination. The modules of four 1x1 $cm^2$ GaSb cells connected in parallel and in series are intended for operation in the generator with an emitter 30-35 mm long. Output power of the both type arrays did not noticeably differ and was about 5 W at the photocurrent density of 5 $A/cm^2$ (measurements at pulsed illumination). The fill factor of the arrays at the current density of about 1 $A/cm^2$ have the maximum value of 69 % (parallel connection). Output power of the arrays at such a current density was about 1.2 W.

Other version of the array has been designed to include a series-parallel (2x2) scheme for connecting four cells using the shingling concept. Such an arrangement of photocells allows to reduce the shadowing losses as well as to utilize more efficiently the area occupied by the photodiodes on a heat removal plate. Terraced ceramics with a conducting silver layer was used for series connection of four 8x9 $mm^2$ GaSb cells with a rear face bar.

Finally, an advanced PV module has been built and tested in real operating conditions. The module body consists of 8 separate heatsinks with arrays mounted through $Al_2O_3$ ceramic plates. The whole solar TPV system was examined in real operating conditions, and an advanced TPV receiver has been built and tested. The power output of 3.1 W has been measured with a module fragment (4 series connected arrays of 4 connected in parallel GaSb cells) in the solar TPV regime ($E_{DIR}$=880W/$m^2$). This corresponds to 6.2 Watts of the total power output available with the full-sized receiver. The power estimated for the full module in the gas-fired (mixed source) regime is 9.8 W. The developed system has relatively small dimensions with the power output of 5-10 Watts. Such a system can utilize the solar radiation saving the fuel. Our preliminary estimations of the system performance reveal approx. 30 % of the fuel economy at the dual source operation.

# IR POWER BEAMING

## GaSb Cells and IR Power Beaming

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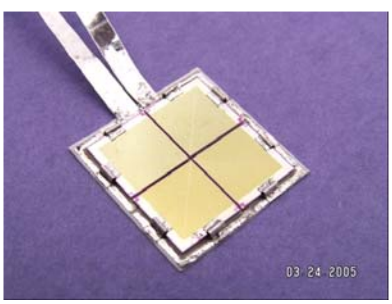
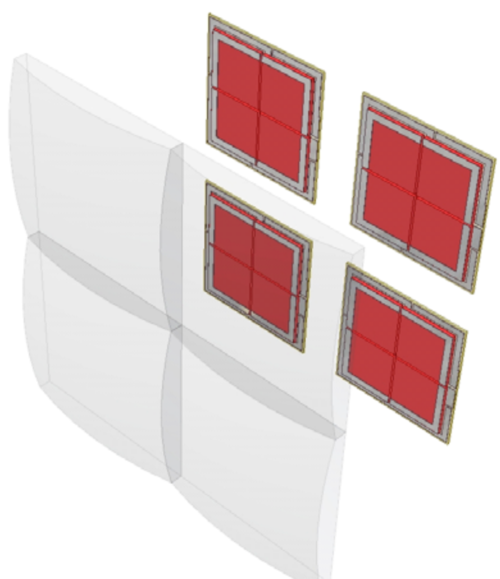
There are two problems impeding the commercialization of TPV systems. The first problem is the development of a complete TPV system for any application. TPV systems require the devlopment of multiple components such as IR emitters and burners in addition to the cells. However, the second problem will be the availability of low cost IR cells. While GaSb diffused junction cells are potentially low cost, this will only be the case if they are fabricated in high volume. Therefore, we are looking for a high volume application for GaSb cells where all of the system components are already available in high volume production. IR power beaming is one such possible application. Eye-safe IR InGaAs diode lasers emitting power beams at 1.6 microns are available as a result of their use in fiber optics communications. With simple optics, a 30 W collumated 5 cm x 5 cm power beam can be created and a GaSb IR cell and lens array can then produce 16 W at 6 V as shown below.

## GaSb Circuits with 1.6 micron IR Power Beaming (16 W at 6 V)



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|---|---|
| FF | 0.682 |
| Voc | 2.046 |
| Isc | 3.063 |
| Pmax | 4.273 |
| Cell Area | 0.49 |
| Receiver Area | 1.96 |
| 1 sun Isc | 0.0092 |
| Suns | 331.85 |