A HIGH-EFFICIENCY MILLIMETER-SCALE THERMOPHOTOVOLTAIC GENERATOR

THERMO PHOTOVOLTAIC GENERATION OF ELECTRICITY

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A millimeter-scale thermophotovoltaic generator was built and characterized. The generator consists of a MEMS microreactor with integrated 1D photonic crystal, four 0.54 eV InGaAsSb cells, and a maximum power point tracker. The microreactor is a 1 cm square of silicon with a serpentine channel etched through it. The channel is loaded with a platinum catalyst that supports combustion of propane in oxygen. A silicon/silicon dioxide stack deposited directly on the microreactor enhances above-bandgap thermal emission and suppresses below-bandgap emission. The maximum power point tracker steps up the voltage from InGaAsSb array to 3.6 volts while providing on-the-fly impedance matching between the cells and the load to ensure the cells are always operating at their maximum power point. With a fuel input of 10 W, the microreactor reaches approximately 800°C. At this operating point, the system has demonstrated fuel to electricity efficiencies of over 2% and delivers 220 mW to the load. With several simple improvements to the system, efficiencies of 3-4% should be achievable at similar operating conditions.

1 INTRODUCTION

Our motivation is to build a high energy density, small scale, static power source. Hydrocarbon fuels offer such a high energy density (12 kWhr/kg) that a even relatively inefficient generator can significantly exceed the performance of state of the art batteries (200 Whr/kg). A hydrocarbon-fueled micro-TPV generator would have obvious applications in extending battery lifetimes for ever increasingly power hungry portable consumer, military, and medical electronics as well as in remote sensing. To this end, we have constructed a millimeter-scale propane-fired TPV generator capable of outputting 220 mW at a fuel-to-electricity efficiency of 2%. The generator consists of four components: a MEMS catalytic microreactor, a photonic crystal deposited directly on the microreactor, low bandgap TPV cells, and a maximum power point tracker. The microreactor and TPV cells in the experimental setup are visible in Fig. 1.

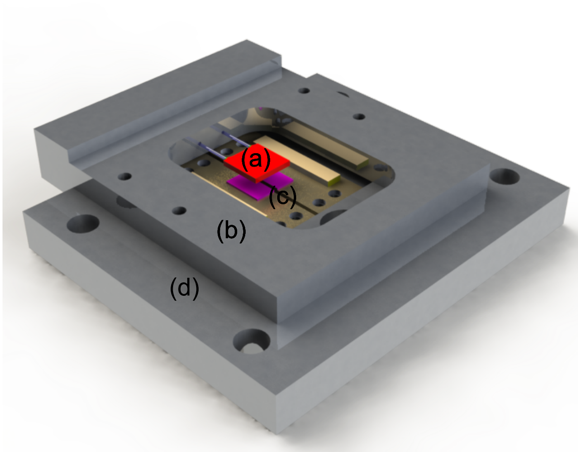

FIG. 1: Render of the TPV system with the top cells removed. The microreactor with integrated photonic crystal (a) is mounted in a metal frame (b). The cells (c) are mounted to an aluminum heat sink (d).

The heat source in our TPV system was a microreactor developed by Brandon Blackwell [1] and based on previous work by the same group [2, 3]. The microreactor was a 10 mm by 10 mm by 1.3 mm silicon slab with a serpentine channel running through it. The channel was wash coated with a platinum catalyst supported on porous alumina. The catalyst was active on propane in oxygen at elevated temperatures. Catalytic combustion is advantageous because it occurs on the channel walls where heat is readily conducted to the emitter. Moreover, homogeneous combustion is difficult to achieve at these length-scales [4]. The microreactor was supported by thin glass capillary tubes that also served as fluidic connections to the channel in order to minimize conductive heat loss. Premixed fuel and oxygen were fed into one capillary; carbon dioxide and water vapor were exhausted from the other.

A nine layer, one dimensional photonic crystal was used to enhance above-bandgap thermal emissions while suppressing below-bandgap emissions. The layer thicknesses were chosen such that the product of the overall system efficiency and power

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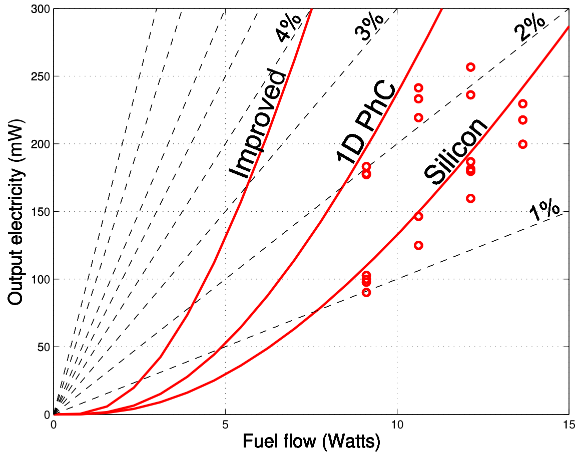

FIG. 2: Electrical power output as a function of fuel flow. The three curves (in ascending order) are for a bare silicon microreactor, a microreactor with a 1D silicon/silicon dioxide photonic crystal, and the photonic crystal plus other improvements described in the text. The dashed lines are lines of constant fuel to electricity efficiencies.

density was maximized [5]. The polycrystalline silicon and silicon dioxide layers comprising the photonic crystal were deposited by a combination of low pressure and plasma enhanced chemical vapor deposition (LPCVD, PECVD) directly on the microreactors. The deposition was done before die sawing and as a result the edges of the microreactors are uncoated.

The TPV cells used in this work are four GaInAsSb cells described in Ref [6]. The $Ga_{1-x}In_xAs_{1-y}Sb_y$ cells were grown by metalorganic vapour phase epitaxy (MOVPE) at Lincoln Laboratory. With $x = 0.15$ and $y = 0.12$, the material has a bandgap of 0.54 eV. The cells have a 1 μm n-GaInAsSb base, 4 μm p-GaInAsSb emitter, a AlGaAsSb window layer, and a GaSb contact layer on a n-GaSb substrate [7, 8].

The maximum power point tracker circuit serves two functions: first, it provides real-time impedance matching between the TPV cell array and the electric load. Second, it boosts the 1 volt output of the array to 3.6 volts—the voltage of a lithium battery. The converter has 90% conversion efficiency and 99% tracking efficiency. Tracking efficiency measures how closely the MPPT tracks the true maximum power point of the cells. Conversion efficiency is the ratio of output to input electrical power [9].

2 EXPERIMENT

The experimental setup is shown in Fig. 1. The microreactor was sandwiched between two sets of two TPV cells. Premixed fuel and oxygen are delivered via one capillary tube and exhaust is removed through the other. The tubes are sealed to the reactor frame with epoxy. The cavity containing the microreactor and cells was evacuated to eliminate convection between the microreactor and the walls of the chamber. A drawing of the experimental setup is given in Fig. ??.

Because the platinum catalyst was only active on propane at elevated temperatures, the reactor was preheated to about 400°C by co-feeding hydrogen. Platinum is active on hydrogen at room temperature. Hydrogen is not a practical means of ignition and can be replaced by methanol vapor, or by using homogeneous combustion or electrical resistive heating to preheat the microreactor. Once lit, the hydrogen was shut off and the propane and oxygen flows were ramped up over about ten minutes while recording data. The mixture was fuel lean: a 1.5 times stoichiometric ratio was always maintained.

The microreactor was first tested in vacuum with an IR window replacing the top cells. The microreactor without a photonic crystal can achieve an average surface temperature of 800°C burning 10 sccm (standard cubic centimeters per minute) of propane and 75 sccm of oxygen as measured by an infrared thermometer. The microreactor with the photonic crystal can reach the same temperature with less fuel consumption due to lower heat loss. Directly measuring the temperature is difficult and not particularly useful because we are primarily concerned with heat energy rather than temperature.

We measured power output as a function of propane flow as reported in Fig. 2. Power output was found by measuring an IV (current-voltage) curve of the full array and calculating the maximum power point, or by measuring the IV of half the array (i.e. the top half was replaced with the IR window to measure temperature) and doubling the power output. The MPPT was only used when a real-time readout was needed, but the drop in efficiency incurred by using the MPPT would be negligible.

The experiment was done for microreactors with and without photonic crystals. A peak conversion efficiency of 2.2% was achieved with a photonic crystal emitter and 1.8% was achieved with a bare silicon emitter, both at a power level of about 220 mW. The discrepancy between the measured and predicted power is probably due to the difference in temperature—we model the reactor as a single average temperature but the temperature is in fact nonuniform. The 1D photonic crystal curve falls away from the model as the power increases because the epoxy sealing the capillary tubes to the reactor frame began to burn and spoiled the vacuum.

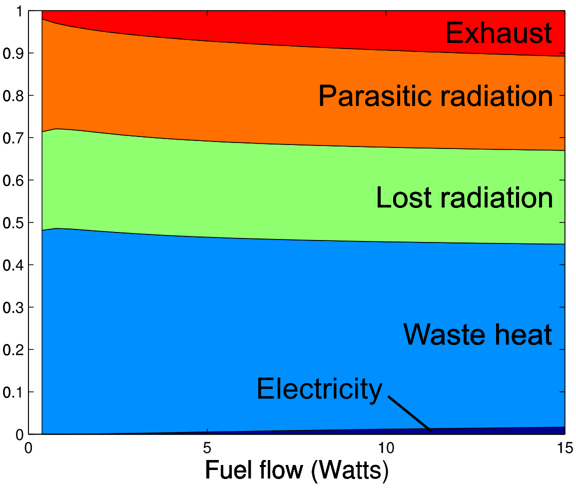

FIG. 3: Breakdown of the heat energy contained in the fuel for the system with the photonic crystal. Exhaust refers to heat lost through the exhaust. Parasitic radiation is power that is radiated away from the cells. Lost radiation is power that is radiated towards the cells but does not reach them. Waste heat is power that reaches the cells but is not converted. Electricity is the usable electricity at the output of the system.

3 DISCUSSION

We used an energy balance model of the TPV system to figure out where the other 98% of the energy was being lost [10]. The heat loss breakdown is shown in Fig. 3. Under typical operating conditions about half the energy contents of the fuel are dissipated as waste heat in the TPV cells due to below-bandgap photons, thermalization of above-bandgap photons, and electrical loses. About 40% is wasted on photons that never reach the cells: they are either radiated from the edges of the microreactor (parasitic radiation) or lost in transit to the cells due to non-unity view factor (lost radiation). Ten percent of the power is sent out the exhaust. The 2% that ends up as electricity seems almost insignificant in the overall energy balance. The energy balance changes slightly when using the photonic crystal emitter because the less power is radiated towards the cells. The parasitic radiation increases because the edges of the microreactor are uncoated and have a higher average emissivity.

The loss breakdown provides insight into the best strategies to increase efficiency. Improving the view factor and reducing the parasitic radiation losses are relatively easy ways to improve efficiency. View factor is a function of the separation between the microreactor and the cells: a smaller separation will increase efficiency. Parasitic radiation can be suppressed by metallizing the die-sawed edges. Although not included in Fig. 3, vacuum packaging will prevent the system from failing at high power levels. Increasing the power is probably the best way to improve performance because it simultaneously improves power density and efficiency. With these improvements in place, an efficiency of 3-4% should be achievable, as shown in Fig. 2.

3 CONCLUSION

We achieved a 2.2% fuel to electricity conversion efficiency at a power output level of 220 mW with a millimeter scale thermophotovoltaic power generator. The heat source was a catalytic silicon MEMS microreactor capable of burning many gaseous fuels in oxygen although we used propane in this work. A one dimensional silicon/silicon dioxide photonic crystal was deposited directly on the microreactor to improve spectral efficiency. We used four InGaAsSb cells. The microreactor was 1 cm^2 and the cell array was 2 cm^2 with half on each side of the microreactor. We can increase the performance to 3-4% with a few tweaks.

The project is motivated by the desire for a high energy density portable power source. While 3% may not sound impressive, a 3% efficient propane fueled generator would have nearly three times the energy density of typical lithium batteries, neglecting the generator weight. This project still has one major hurdle before becoming truly viable: the propane is burned in oxygen instead of air. Carrying both the fuel and oxidizer goes against the goal of high energy density. It should be possible to design a new microreactor that can reach the necessary temperatures with propane-air combustion. Burning with air has the disadvantage of increasing the loss out the exhaust by a factor of five at a given microreactor temperature. By using a recuperator to transfer heat from the exhaust to the incoming air, the exhaust loses can be brought back to a reasonable level.

[1] B. S. Blackwell, Ph.D. thesis, Massachusetts Institute of Technology (2008).
[2] O. Nielsen, Ph.D. thesis, Massachusetts Institute of Technology (2006).
[3] L. Arana, Ph.D. thesis, Massachusetts Institute of Technology (2003).
[4] A. C. Fernandez-Pello, Proceedings of the Combustion Institute **29**, 883 (2002), ISSN 1540-7489.

[5] P. Bermel, M. Ghebrebrhan, W. Chan, Y. Yeng, M. Araghchini, C. Marton, K. Jensen, M.Soljacic, J. Joannopoulos, S. Johnson, et al., Opt. Express (2010, accepted).

[6] W. Chan, R. Huang, C. Wang, J. Kassakian, J. Joannopoulos, and I. Celanovic, Solar Energy Materials and Solar Cells **94**, 509 (2010), ISSN 0927-0248.

[7] M. W. Dashiell, J. F. Beausang, H. Ehsani, G. J. Nichols, D. M. Depoy, L. R. Danielson, P. Talamo, K. D. Rahner, E. J. Brown, S. R. Burger, et al., Electron Devices, IEEE Transactions on **53**, 2879 (2006), ISSN 0018-9383.

[8] C. A. Wang, H. K. Choi, S. L. Ransom, G. W. Charache, L. R. Danielson, and D. M. DePoy, Applied Physics Letters **75**, 1305 (1999).

[9] R. C. N. Pilawa-Podgurski, N. A. Pallo, W. R. Chan, D. J. Perreault, and I. L. Celanovic, in *Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE* (2010), pp. 961 –967, ISSN 1048-2334.

[10] W. Chan, Master's thesis, Massachusetts Institute of Technology (2010).