A prototype microthermophotovoltaic power generator

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A prototype microthermophotovoltaic (micro-TPV) power generator is described in this letter. The system is made of a SiC (silicon carbide) emitter, a simple nine-layer dielectric filter, and a GaSb (gallium antimony) photovoltaic cell array. In a microcombustor of 0.113 cm^3 in volume, when the flow rate of hydrogen is 4.20 g/h, the micro-TPV system is able to deliver an electrical power output of 1.02 W, corresponding to an open-circuit electrical voltage of 2.28 V and a short-circuit current of 0.59 A. The prototype of the micro-TPV system will make it possible for us to substitute batteries with micropower generators in micromechanical devices in the near future. [DOI: 10.1063/1.1751614]

The last few years have experienced a growing trend in the miniaturization of mechanical and electromechanical engineering devices. All kinds of microdevices such as micropumps, micro-motors, micro-robots, micro-rovers, and micro-airplanes are being developed. However, the miniaturization of these devices is limited by the weight of the available power systems (batteries) that occupy significant fractions of both mass and volume of the entire devices. Typical portable mechanical devices also suffer from short operation cycles between charges or replacement. The need to reduce system weight, increase operational lifetimes is behind the emergence of a new class of microelectromechanical system devices, micropower generators characterized by thermal, electrical, and mechanical power density of 1–20 W in subcentimeter-sized packages.[1]

It is well known that hydrocarbon fuels have energy densities much greater than the best batteries. Therefore, taking advantage of the high energy density of chemical fuels to generate power becomes an attractive technological alternative to batteries. Micro-gas turbine engine,[2] micro-rotary engine (Wankel-type),[3] micro-thermoelectric[4] and micro free piston knock engine[5] are typical micropower generators being developed recently. The above-noted micropower systems experience one major challenge, high heat losses due to the high surface-to-volume ratio. According to the cubic-square law, when the size of a combustor decreases by a factor of 100, the surface to volume ratio will increase by a factor of 100. With the same heat flux density per unit surface, the heat flux via the wall will increase by a factor of 100 per unit volume for microccombustor.

The microthermophotovoltaic (micro-TPV) system is a micropower generator which uses photovoltaic (PV) cells to convert heat radiation, e.g., from the combustion of fossil fuels, into electricity. For micro-TPV application, the desired output is a high and uniform temperature along the wall of the microcombustor, therefore, a high surface-to-volume ratio is very favorable to the output power density per unit volume, which makes the study of micro-TPV systems particularly attractive.

A prototype micro-TPV power generator has been built-up and tested in NUS (National University of Singapore). The system mainly consists of (1) a heat source, (2) a cylindrical SiC emitter with emissivity of 0.9 (i.e., microcombustor), (3) a simple nine-layer dielectric filter, and (4) a GaSb photovoltaic cell array. Furthermore, cooling fins are attached on the back of the PV cells to remove the sink heat by the PV cells. Figure 1 shows two pictures of the micro-TPV system, where the cylindrical SiC emitter is not incorporated into the system. H_2/air mixture is combusted in the cylindrical SiC microcombustor. As the wall of the microcombustor (i.e., SiC emitter) is heated to a sufficient high temperature, it emits a lot of photons. When they impinge on the GaSb PV cell array, they would evoke free electrons and produce electrical power output. The system does not involve any moving parts, its fabrication and assembly are relatively easy. Therefore, it can be widely used in commercial electronics and microdevices.

Microcombustor is the first key component of micro-TPV systems. The major challenge in the design of microcombustor is to keep an optimal balance between maximizing heat radiation output and sustaining stable combustion. A high surface-to-volume ratio is very favorable to the output power density per unit volume. However, sustaining combustion will be greatly affected by the increased heat losses that tend to suppress ignition and quench the reaction. To testify to the feasibility of micro-combustion and optimize the design of microcombustor, a series of numerical simulations and experiment work were carried out. Results indicate that a microcylindrical combustor with a backward facing step is one of the simplest but most effective structures for the micro-TPV application. Because the backward facing step can facilitate recirculation along the wall and enhance the mixing process around the rim of the tube flow, at the beginning stage, combustion takes place near the wall rather

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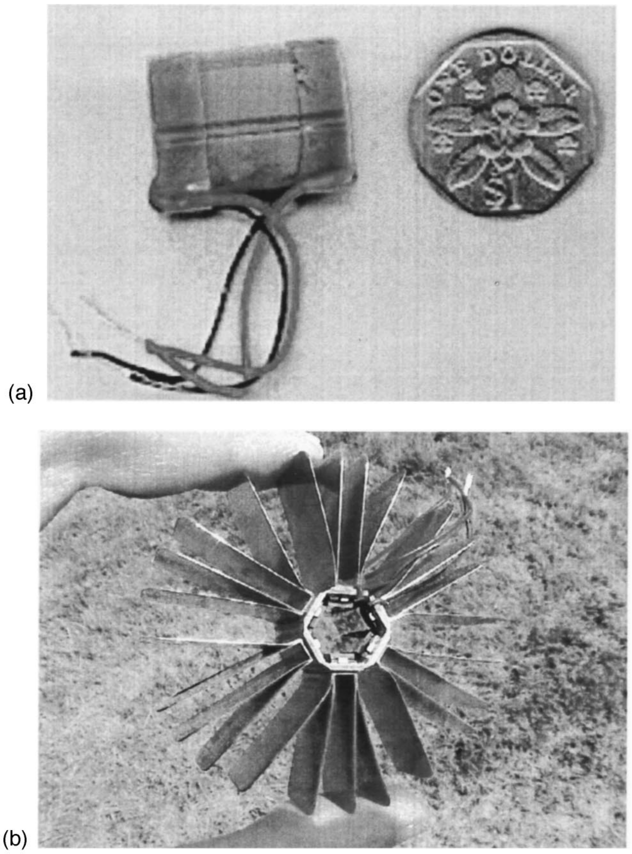

FIG. 1. Prototype micro-TPV power generator without microcombustor (a) without cooling fins, (b) with cooling fins.

than the center region. The H_2/air mixture in the central region is then heated and accelerated by the hot combustion products around it, and flows to the central region near the exit and combusts, which inversely heat the gas near the wall, and thereby maintain a fairly uniform temperature along the wall. Furthermore, for the micro-TPV application, the microcombustor should have good emissivity and can endure high temperature. Based on the above-noted considerations, a cylindrical SiC combustor with a backward facing step is designed and fabricated for the micro-TPV system. In a micro-cylindrical SiC combustor of 3 mm in diameter, 16 mm in length, and 0.3 mm in wall thickness, an average temperature of 1325 K has been obtained along the wall, and the biggest difference of temperature is less than 5%, when the H_2 flow rate is 4.20 g/h and the H_2 /air ratio is 0.9. The volume of the microcombustor is 0.113 cm^3. Figure 2 shows the picture of combustion under the above-noted conditions, it is taken by digital camera.

The second key component of the micro-TPV system is a simple nine-layer dielectric filter. The SiC emitter is a typical broadband emitter. The spectrums of broadband emitters operating at temperatures of 1000–1600 K contain significant proportions of subband gap photons with energies not sufficient enough to generate charge carriers in the PV cells. This portion of energy will be absorbed by the PV cells and result in a destructive heat load on the generator components, subsequently lowering conversion efficiency of the system. In order to improve the overall efficiency of the micro-TPV system, it is very important to recycle these photons. So a filter should be employed in the micro-TPV system. Ideally,

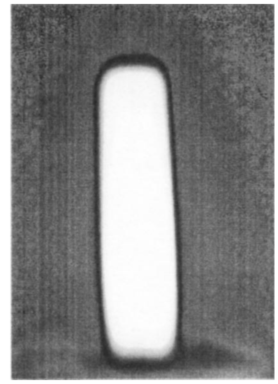

FIG. 2. Picture of microcombustion (H_2 flow rate is 4.2 g/h, H_2/air ratio is 0.9).

the filter should be able to reflect all nonconvertible photons back to the emitter and transmit all convertible photons to the PV cell array. However in practice, it is very hard to achieve. Here, a simple nine-layer dielectric filter is designed and fabricated for the micro-TPV system. The filter is able to recycle the energy emitted in the 1.8–3.5 μm mid-wavelength band. Figure 3 shows the reflectance of the filter. The filter is fabricated with alternating layers of silicon and silicon dioxide, and is deposited on glass slide and bonded on the top of GaSb PV cells with silicone. The thickness of the filter is 0.102 mm. This kind of method makes the assembly of micro-TPV system very easy.

The third key component of the micro-TPV system is a low band gap PV cell array. Compared to PV conversion of solar energy, the photons emitted from a heat source at 1000–1600 K are distributed at much lower energies and longer wavelengths. This necessitates the use of low band gap semiconductors for the TPV energy conversion diode, in order to simultaneously maximize both the efficiency and the power density. Although the concept of TPV energy conversion was first proposed in the 1960s,[6] it was only in recent years that technological improvements in the field of low band gap photovoltaic cells and high temperature materials have evoked a renewed interest in TPV generation of electricity.[7] GaSb,[7] GaInAs (gallium, indium, and arsenic),[8] and InGaAsSb (indium, gallium, arsenic, and antimony)[9] are typical low band gap PV cells developed recently for TPV applications. Corresponding to the filter, a GaSb PV cell array is designed and fabricated for our micro-TPV system. This GaSb cell array responds out to 1.8 μm. The process used to fabricate the above-mentioned GaSb cells replicates the silicon solar cell fabrication process, using inexpensive diffusion steps with no toxic gases, in contrast to epitaxy.

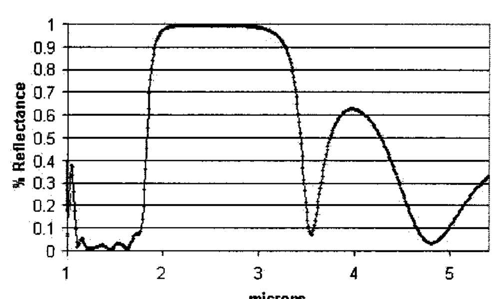

FIG. 3. The reflectance of a simple nine-layer dielectric filter.

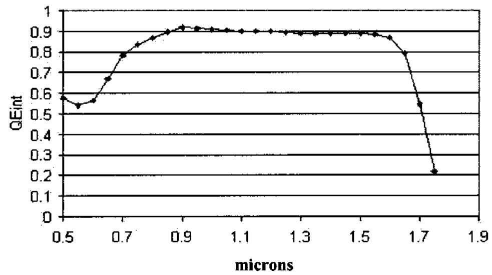

FIG. 4. Internal quantum efficiency of GaSb PV cell.

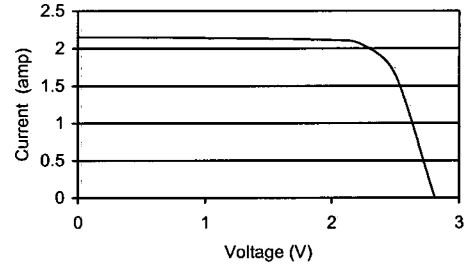

FIG. 5. $I-V$ curve of the GaSb PV circuit.

The internal quantum efficiency of the GaSb cell is shown in Fig. 4. Because only planar GaSb PV cells can be fabricated, the array is composed of six 4.5 mm×18 mm planar GaSb PV cells forming a cylindrical tube, see Fig. 1. The active area is 4.3 mm×15.5 mm for each cell. The filter face-to-face distance is 8.4 mm.

The performance of the GaSb PV circuit is measured with a flash lamp solar simulator. The results indicate the GaSb PV circuit offers a very good electrical conversion performance. A maximum electrical power output of 4.60 W has been achieved for the GaSb PV circuit, corresponding to a 2.24 V voltage and a 2.05 A current. The open-circuit voltage and short-circuit current are 2.81 V and 2.15 A, respectively. While the fill factor of the GaSb PV circuit is 0.761. The $I-V$ curve of the GaSb PV circuit is shown in Fig. 5.

The electrical power output of the prototype micro-TPV system incorporated with a SiC emitter is then measured for all kinds of flow rate and H_2/air ratio. From the experiment we can draw some conclusions.

When the flow rate at the inlet of the microcombustor is constant, with an increase in H_2/air ratio, the electrical power output of micro-TPV system increases drastically, especially when the H_2/air ratio is lower than 0.9. This is because more fuel takes part in combustion, subsequently increasing the temperature along the wall of microcombustor. While the H_2 /air ratio varies from 0.9 to 1.0, the increase of electrical power output is not so apparent, because there is only a small increase in the wall temperature of microcombustor.

When the H_2/air ratio is constant, with an increase of the flow rate, the electrical power output of micro-TPV system also increases drastically due to more fuel participating combustion.

As the hydrogen flow rate is 4.20 g/h and the H_2/air ratio is 0.9, an electrical power output of 1.02 W has been achieved for the micro-TPV system. The open-circuit voltage and short-circuit current are 2.28 V and 0.59 A, respectively.

During experimenting, we also find that the temperature along the wall of microcombustor remains nearly uniform when the length of microcombustor is increased to 22 mm, at the hydrogen flow rate of 4.20 g/h and the H_2/air ratio of 0.9. This is due to the reflection of filter. Therefore, a 1.45 W electrical power output can be obtained if we increase the active length of GaSb PV cells from 15.5 to 22 mm. The volume of the microcombustor will be 0.155 cm^3.

Furthermore, in order to further increase the output electrical power density and improve the efficiency of micro-TPV system, it is necessary to employ a selective emitter in future design of micro-TPV systems instead of a SiC broadband emitter. For the last decade, several methods have been developed to fabricate selective emitters. One familiar way is to use oxides of rare earth materials such as erbia (Er_2O_3) and ytterbia (Yb_2O_3).[10] Another way is microstructuring the surface of the emitters.[11] Recently, a matched emitter[12] has been developed at the University of Washington. This kind of emitter exhibits a high emittance in the spectral range usable for the PV cell, and a low emittance elsewhere. If such a matched emitter is employed in the micro-TPV systems, then an electrical power output of 5.5 W can be expected in a microcombustor of 0.155 cm^3 in volume.

In summary, a prototype micro-TPV power generator is described in this letter. The system is made of a SiC emitter, a simple nine-layer dielectric filter, and a GaSb Photovoltaic cell array. In a microcombustor of 0.113 cm^3 in volume, when the flow rate of hydrogen is 4.20 g/h and the H_2/air ratio is 0.9, the micro-TPV system is able to deliver an electrical power output of 1.02 W, corresponding to an open-circuit electrical voltage of 2.28 V and a short-circuit current of 0.59 A. The electrical power output can be further increased to 5.5 W in a microcombustor of 0.155 cm^3 in volume, if a matched emitter is employed in the micro-TPV system. The prototype of the micro-TPV system will make it possible for us to substitute batteries with micropower generators in micromechanical devices in the near future. It is very interesting to the development of all kinds of microdevices.

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