Selective-emitter-enhanced Micro Thermophotovoltaic Power Generation System

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ABSTRACT

Ti-coated Si microcavities with extremely-smooth sidewalls has been developed using DRIE and vacuum arc evaporation for improvement of energy conversion efficiency of micro thermophotovoltaic system. For 1.8 μm microcavities, the peaks in emittance spectra correspond well to the electromagnetic resonance modes. Micro cavities designed for Ge photovoltaic cells are also successfully microfabricated. It is found that estimates of the energy conversion efficiency of Ge PV cell are increased to 6.4 % and 13 % respectively for the emitter temperature of 900 and 1200 °C.

INTRODUCTION

With increasing demand for high-density energy source of portable electric devices, fuel-based micro power generators attract significant attention as an alternative to lithium-ion batteries. Thermophoto-voltaic (TPV) is one of the promising such systems due to its large power generation density, compatibility to various kinds of fuels, and simple configuration without moving parts. However, its energy conversion efficiency remains low because of the spectral mismatch between the emission spectra from combustor and the band gap of photovoltaic (PV) cells. Thus, spectrum control of the thermal emission is a key issue for high-efficiency TPVs. As shown in Fig. 1, micro TPV system will consist of micro combustor, selective emitter, low-bandgap PV cell, heat exchanger for thermal recycle, and vacuum package for minimum heat loss.
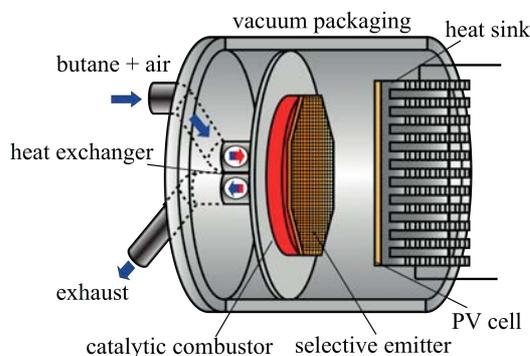

Figure 1. Micro TPV power generation system.

Sai et al. [1] and Hanamura et al. [2] separately developed surface microcavities for radiation spectral control by using FAB or lost-mold electroplating. They reported spectral emission increase in the resonance modes. However, more cost-effective fabrication methods should be employed for devices with large area. We previously reported that the surface roughness of the cavity wall has large effect on the electromagnetic resonance [3].

In the present study, Ti-coated Si microcavities are microfabricated and its performance is examined. In addition, the energy conversion efficiency of the micro TPV system is estimated.

DESIGN AND FABRICATION OF SILICON MICROCAVITY

Electromagnetic resonance modes in the rectangular microcavities [4] is expressed by

$$\lambda_{lmn} = \frac{2}{\sqrt{\left(\dfrac{l}{L_x}\right)^2 + \left(\dfrac{m}{L_y}\right)^2 + \left(\dfrac{n}{2L_z}\right)^2}}$$

$$l, m = 0,1,2,3..., \text{ and } n = 0,1,3,5..., \tag{1}$$

where L_x and L_y are the widths of microcavity openings, while L_z is the depth of cavity. The maximum value of λ_{lmn} corresponds to the wavelength of the first resonance mode λ_r. Based on
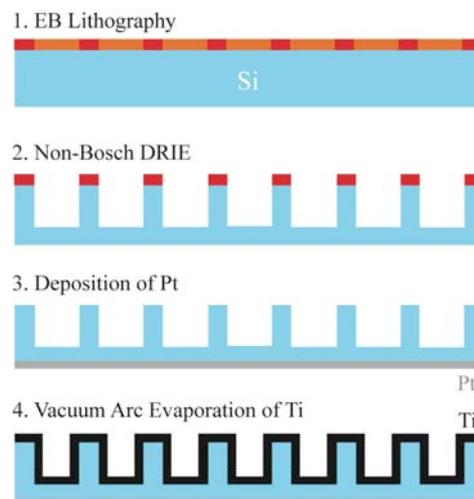

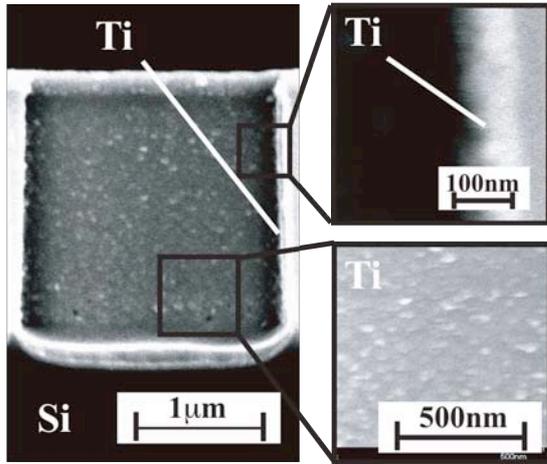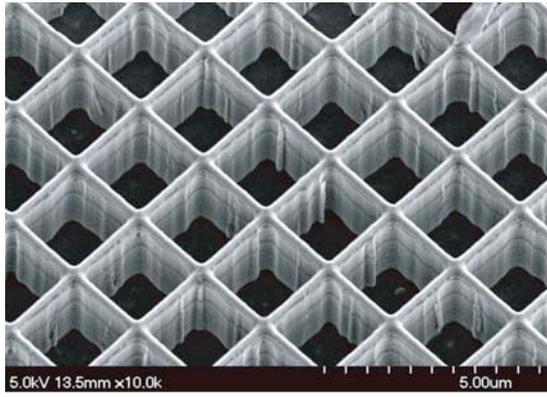Figure 2. Process flow of Ti-coated Si microcavities.

Figure 3. Ti-coated Si microcavity fabricated with EB lithography and vacuum arc evaporation.

Eq. (1), we designed two microcavities, i.e., $L_x = L_y = L_z = 1.8\mu m$ (λ_r=3.2 μm) and $L_x = L_y = L_z = 0.7$ μm ($\lambda_r = 1.25$ μm).

Figure 2 shows the process flow of the present Si microcavities. Firstly, 400-nm-thick EB resist (ZEP-520A, ZEON Chemicals) is spun on at 4000 rpm, and exposed with an ultra-fast EB lithography system (F5112+VD01, ADVANTEST). After development, microcavities are etched into the Si substrate with continuous SF_6 plasma using DRIE (MUC-20, Sumitomo Precision Products) in order to get vertical yet smooth sidewalls. Finally, after sputtering of Pt on the backside to prevent infrared light transmission through the Si substrate, Ti layers are deposited using inclined physical vapor deposition at four different rotation angles. In the present study, we employ vacuum arc evaporation (ARL-300, ULVAC) [5], in which nano particles of Ti can be produced with arc discharge.

Figure 3 shows SEM images of the Ti-coated Si microcavities. The surface roughness of the cavity wall is much smaller than the Ti layer with EB evapolation [3].
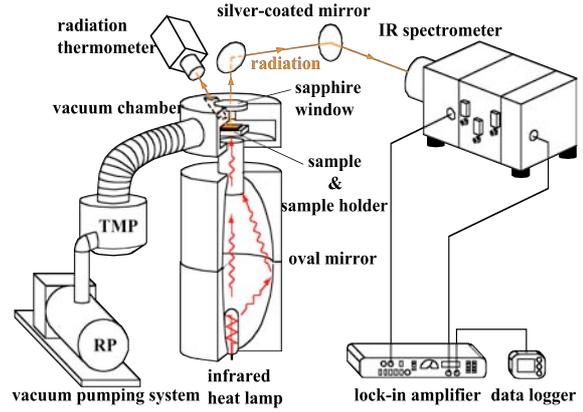

Figure 4. Experimental setup.

RADIATION SPECTRUM MEASURE-MENT

Figure 4 shows the experimental setup for the radiation spectrum measurements, which consists of a vacuum chamber with a sapphire window, an infrared heat lamp (GVL298, Thermo Riko), a graphite sample holder, an infrared spectrometer (MC-10N3G, Ritsu Applied Optics), and a radiation thermometer (KT 15.02, Heitronics). The sample is placed in the vacuum chamber to prevent heat loss and oxidization, and heated up to about 800 °C at 2×10^{-3} Pa with the infrared heat lamp from the bottom. Thermal radiation from the sample is introduced to the spectrometer with a series of mirrors. A lock-in amplifier (SR510, Stanford Research Systems) is employed to measure the output voltage of the spectrometer.

Emittance of the sample (ε_{sam}) was calculated using the radiation energy of the sample (E_{sam}) and that of a reference material (E_{ref}) with known emittance (ε_{ref}). In the present study, blackbody paint (JSC-3, Japan Sensor) with the emittance of 0.94 was used. Emittance of the sample is determined by

$$\varepsilon_{sam}(\lambda) = \varepsilon_{ref}(\lambda)\frac{E_{sam}(\lambda)}{E_{ref}(\lambda)}\frac{\exp\left(\dfrac{hc}{kT_{sam}\lambda}\right)-1}{\exp\left(\dfrac{hc}{kT_{ref}\lambda}\right)-1}, \quad (2)$$

where h, c, k, λ and T are respectively Planck's constant, the light speed, Boltzmann constant, the wavelength and the sample temperature measured with the radiation thermometer.

Since Si substrates are transparent in the infrared region, the Ti layers must be thicker than the skin depth [6], in order to obtain reflection on the sidewall and thus the electromagnetic resonance. Figure 5 shows emittance spectra of the 1.8 μm microcavities at 800 ˚C for different Ti thicknesses. Emittance peaks of both microcavities correspond well to the
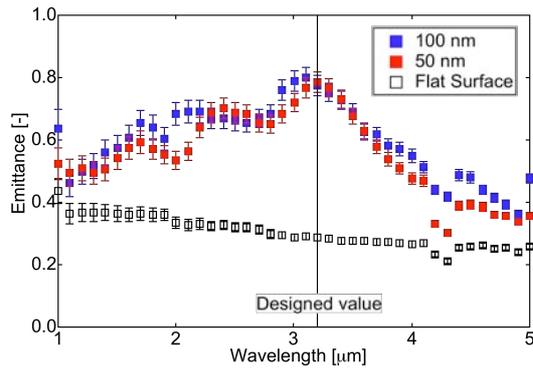
Figure 5. Emittance spectra of 1.8 µm microcavities at 800 ˚C for different Ti thickness.

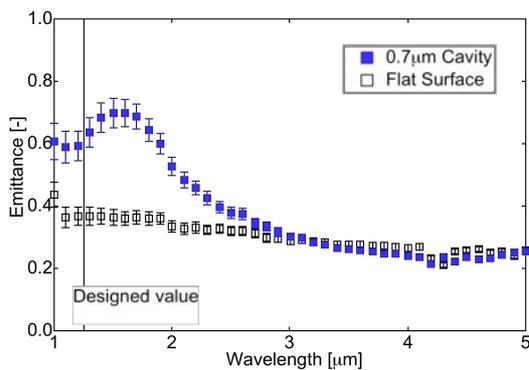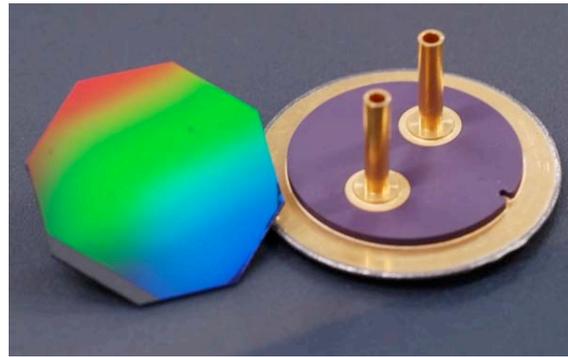Figure 6. Emittance spectra of 0.7 µm microcavities at 800˚C.

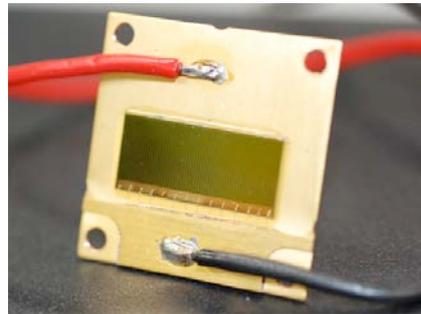Figure 7. Selective emitter prototype (left) and micro catalytic combustor (right)

Figure 8. Low-band-gap Ge PV cell (λ_{BG} =1.94µm) developed by Fraunhofer ISE [5].

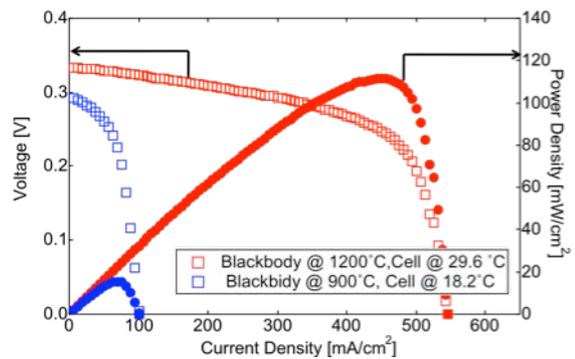Figure 9 I-V characteristics of Ge PV cell with a black body emitter at 900 ˚C and 1200 ˚C.

electromagnetic resonance modes (Eq. 1). Agreement of emittance spectra of both microcavities indicates that 50 nm is sufficient for the Ti thickness.

Figure 6 shows the emittance spectra of the 0.7 µm cavity with 50-nm-thick Ti coating at 800 ˚C. Emittance is much increased in short wavelength region if compared with that of flat surface, although the emittance peak is somewhat shifted to longer wavelength than its designed value. It is noted that the emittance in the longer wavelength remains unchanged and is almost the same as that of the flat surface.

Figure 7 shows a micro catalytic combustor fabricated with ceramic tape-casting [7] together with the present selective emitter. The combustor with Pd catalyst/nano-porous alumina support can provide uniform wall temperature for butane fuel, and gives 40-50 W heat generation. By optimizing the arrangement of the catalyst and structures, its maximum operation temperature is as high as 900 °C even with catalytic combustion.

ENERGY CONVERSION EFFICIENCY WITH GE PV CELL

As a low-band-gap TPV cell, we employ a Ge PV cell developed by Fraunhofer ISE (Fig. 7), of which wavelength corresponding to the band gap is λ_{BG} =1.94 µm [8]. Performance of the Ge PV cell is examined with a blackbody emitter as shown in Fig. 9. In this experiment, the distance between the blackbody emitter and the PV cell is 10 mm, so that the view factor is as low as 0.18. Power density of 15 and 110 mW/cm^2 is obtained respectively at the emitter temperature of 900 ˚C and 1200 ˚C. In the following section, we made an estimate for energy conversion efficiency of the present TPV system.

Table 1. Conversion efficiency of the TPV system estimated with the present emitter.

Emitter temperature	900 ˚C	1200 ˚C
Present microcavity	6.4 %	13 %
Blackbody emitter	3.0 %	7.4 %

Using an equivalent circuit model of PV cell, the short current density of the PV cell (J_{sc}) can be written as

$$J_{sc} = qF \int_0^\infty \frac{Q(\lambda)\varepsilon_{sam}(\lambda)W(\lambda)}{hc/\lambda} d\lambda, \qquad (3)$$

where q, F, and $Q(\lambda)$ are respectively the elementary charge, the view factor, the quantum efficiency. Radiation spectra of blackbody is given by Planck's law, i.e.,

$$W(\lambda) = \frac{2\pi hc^2}{\lambda^5} \left[\exp\left(\frac{hc}{kT_{sam}\lambda}\right) - 1 \right]^{-1}. \qquad (4)$$

The open current voltage (V_{oc}), the voltage at maximum power point (V_{mp}), and the maximum power (P_{max}) are expressed by

$$V_{oc} = \frac{kT_{cell}}{q} \ln\left(\frac{J_{sc}}{J_0} + 1\right), \qquad (5)$$

$$V_{oc} = \frac{kT_{cell}}{q} \ln\left(1 + \frac{qV_{mp}}{kT_{cell}}\right) + V_{mp}, \qquad (6)$$

and

$$P_{max} = \frac{qJ_{sc}(V_{mp})^2}{(kT_{cell} + qV_{mp})}, \qquad (7)$$

where J_0 and T_{cell} are the dark current density and the temperature of the PV cell, respectively [9]. Thus, theoretical conversion efficiency is expressed by

$$\eta = \frac{P_{max}}{\int_0^\infty \varepsilon_{sam}(\lambda)W(\lambda)d\lambda}. \qquad (8)$$

The dark current density J_0 depends on the temperature of PV cell and is expressed by

$$J_0 = AT_{cell}^3 \exp\left(-\frac{B}{T_{cell}}\right), \qquad (9)$$

We made a series of experiments for different cell temperature, and determined constants A and B in Eq. (9) using a weighted least-square method.

Here, we assume that both the emitter area and the PV cell area are 700 mm^2, and the distance between them is 2 mm, which results in the view factor of 0.87. Energy conversion efficiency defined as the ratio of the electric power generated to the radiation energy from the emitter is estimated with Eqs. (4-8) at the cell temperature of 25 ˚C. Table 1 summarizes the conversion efficiency with/without the selective emitter. The energy conversion efficiency with the present microcavities at 900 ˚C is 6.4 %, which is

much larger than 3.0 % for the blackbody emitter. By increasing the temperature to 1200 ˚C, the efficiency increases to 13%, which is almost twice as large as that for blackbody emitter.

CONCUSIONS

For a selective emitter of micro TPV system, Ti-coated Si microcavities have been microfabricated with DRIE and vacuum arc evaporation. Emittance peaks in the short-wavelength region are successfully obtained. For a Ge PV cell, estimates of the energy conversion efficiency are increased to 6.4 % and 13 % respectively for the emitter temperature of 900 and 1200 °C.

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