EMISSION SPECTRAL CONTROL USING METAL-COATED SILICON MICROCAVITY FOR THERMOPHOTOVOLTAIC

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Abstract: Metal-coated silicon microcavities have been microfabricated as selective emitter using two different metal deposition methods, electron-beam evaporation and vacuum arc evaporation. Surface roughness of the metal coating with vacuum arc evaporation is much smaller than that with electron-beam evaporation. For both microcavities, an emittance peak appears at the wavelength of 3.2 µm, which corresponds to the designed value. However, for microcavities with vacuum-arc-evaporated metal coatings, the emittance spectrum peaks well corresponds to the electromagnetic resonance modes, while it reduces to the value for smooth surfaces in the long wavelength region. When Ge PV cell is assumed, ideal energy conversion efficiency with the present microcavity at 900 °C is estimated to be 13 %, which is much larger than 6.1% for blackbody emitter.

Keywords: Thermophotovoltaic, Selective emitter, Microcavity, Surface roughness

INTRODUCTION

For power supply of portable electronic devices, lithium-ion battery (LIB) is now widely used. However, its energy density will be insufficient for long-term operation of those devices. In view of future high-performance mobile information and telecommunications devices, fuel-based portable power sources with much larger energy density attract significant attention.

Thermophotovoltaic (TPV) power generation system (Fig. 1) is one of the promising micro power generation 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.

Sai et al. [1] and Hanamura et al. [2] reported electromagnetic resonance on surface microcavities, which enhances emission in the short wavelength region. However, in the previous studies, expensive fabrication methods such as fast atom beam etching are used to develop microcavities on a single crystalline metal surface. We previously reported that metal-coated Si microcavities, which is easily applied to large area, can be used as a selective emitter, and the surface roughness of the cavity wall has large effect on the electromagnetic resonance [3].

In the present study, we investigate metal deposition methods for the metal-coated Si microcavities, and examine the effects of the surface roughness of the cavity wall on the electromagnetic resonance.

EXPERIMENT

Design and Fabrication of Microcavity

Maruyama *et al*. [4] reported that the wavelength of electromagnetic resonance in the rectangular microcavities is expressed as

$$\lambda_r\left(n_x,n_y,n_z\right)=\frac{2}{\sqrt{\left(\frac{n_x}{L_x}\right)^2+\left(\frac{n_y}{L_y}\right)^2+\left(\frac{n_z}{2L_z}\right)^2}}, \qquad (1)$$

where n_x, n_y = 0,1,2,3..., n_z = 0,1,3,5.... L_x and L_y are openings and L_z is depth of the microcavities, respectively. The maximum wavelength of λ_r corresponds to the wavelength of peak emittance. We designed $L_x = L_y = L_z = 1.8$ µm in order to have the emittance peak at the wavelength of 3.2 µm. Assuming Ge PV cell [5], of which bandgap wavelength is 1.94 µm, we also made microcavities with $L_x = L_y = L_z = 0.7$ µm, which corresponds to λ_r = 1.25 µm.

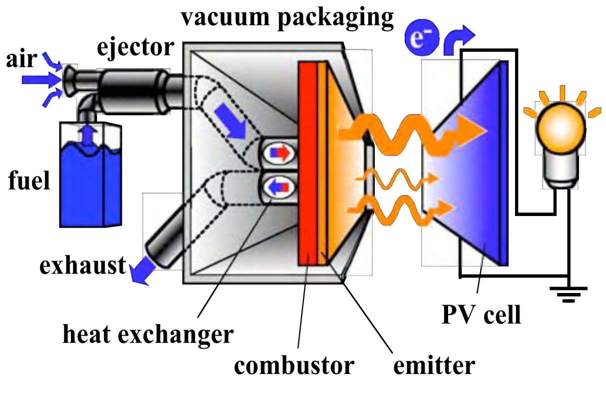

Fig. 1: TPV power generation system.

Figure 2 shows the process flow of the metal-coated Si microcavities. Firstly, 400-nm-thick electron-beam (EB) resist (ZEP-520A, ZEON Chemicals) is spun on at 4000 rpm, baked at 180 ˚C for 15 minutes, and exposed with an ultra-fast EB lithography system (F5112+VD01, ADVANTEST) with a dose of 100 $\mu C/cm^2$. Then, Si microcavities are etched into the substrate with non-Bosch deep reactive ion etching (DRIE) (MUC-20, Sumitomo Precision Products) in order to get vertical yet smooth sidewalls. Finally, after sputtering Pt on backside to prevent infrared light transmission, 50-nm-thick Ti layers are deposited using inclined vacuum arc evaporation (ARL-300, ULVAC) [6] with four different rotation angles. Since vacuum arc evaporation can produce metal particles on the order of nm, the surface roughness of the cavity wall can be much smaller than that fabricated with conventional EB/thermal evaporation.

Figure 3 shows SEM images of the Ti-coated Si microcavities. Figure 4 shows magnified SEM images of the microcavities with the EB and vacuum arc evaporation. Ti layers are uniformly coated even on the sidewalls. For microcavities fabricated with the EB evaporation, the metal layer surface is somewhat rough. The dimensions of the roughness element are on the order of 100 nm. On the other hand, vacuum arc evaporation can produce metal particles on the order of nm, the surface roughness of the cavity wall is much smaller than that fabricated with EB evaporation.

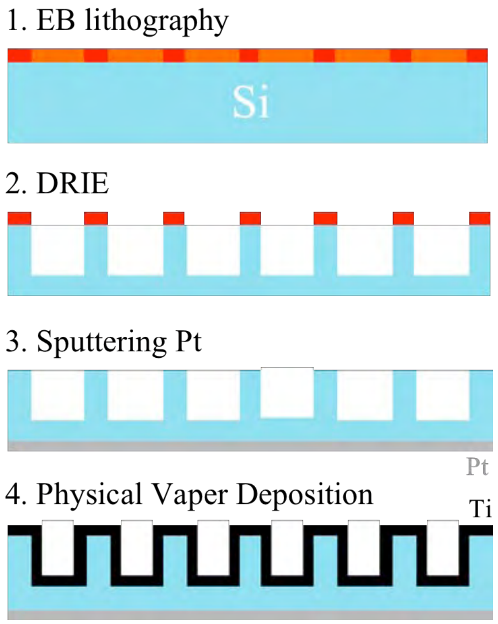

Fig. 2: Process flow of Si microcavities.

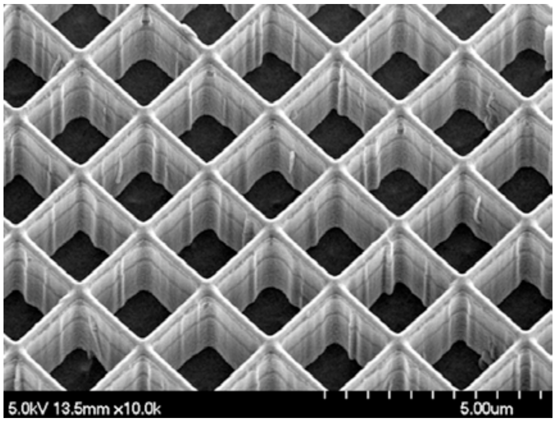

Fig. 3: SEM image of Ti-coated Si microcavities fabricated with vacuum arc evaporation.

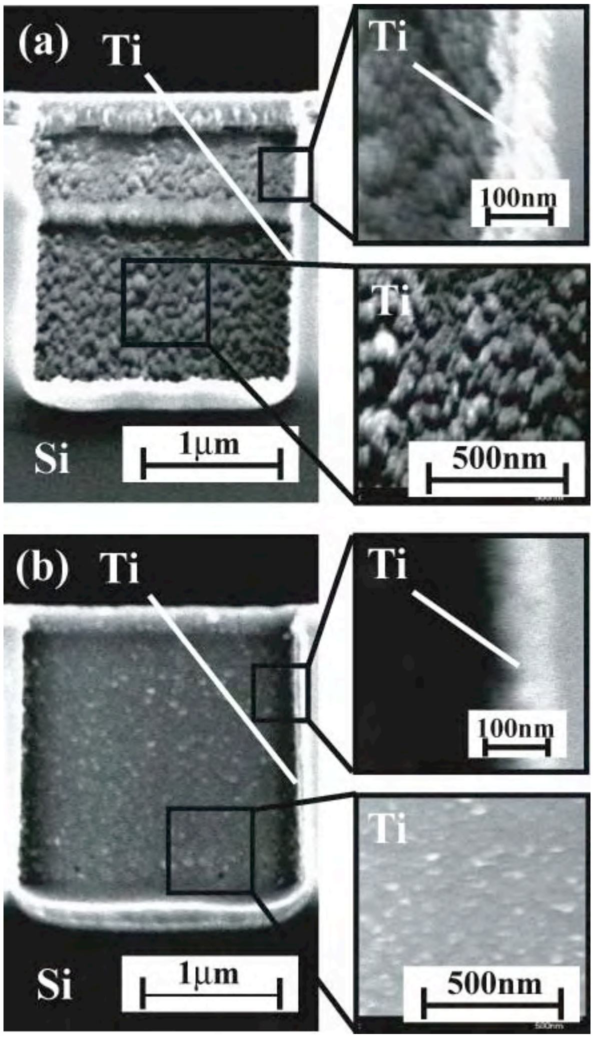

Fig. 4: Si microcavity fabricated with Ti film using (a) EB evaporation, and (b) Vacuum arc evaporation.

Experimental Setup

Figure 4 shows the experimental setup for the emittance spectrum measurements, which consists of a vacuum chamber, an infrared heat lamp (GVL2998, 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 on the graphite holder, and placed in the vacuum chamber with a sapphire window 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 using two silver-coated 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) of which emittance is 0.94 was used. Emittance of the sample is expressed as

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

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

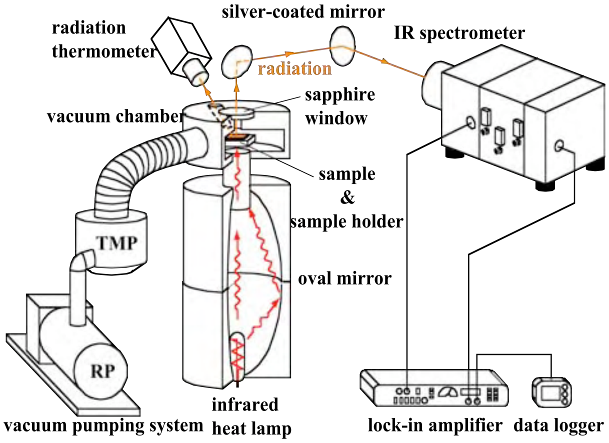

Fig. 5: Experimental setup.

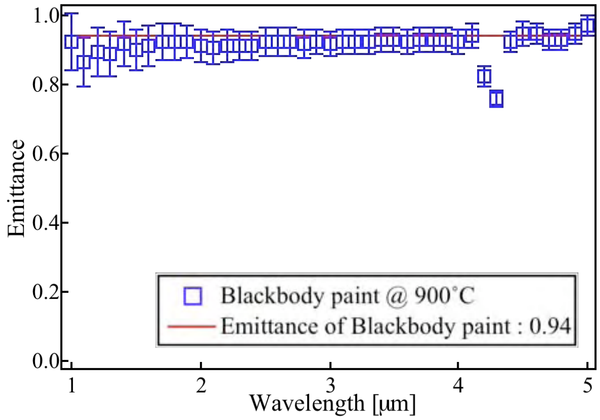

Fig. 6: Experimental results for the emittance of the reference material at about 900˚C.

Uncertainty interval of the emittance can be expressed as

$$\frac{d\varepsilon_{sam}(\lambda)}{\varepsilon_{sam}(\lambda)}=\left[\left|\frac{dE_{sam}(\lambda)}{E_{sam}(\lambda)}\right|^2+\left|\frac{dE_{ref}(\lambda)}{E_{ref}(\lambda)}\right|^2+\left|\frac{hc}{kT_{sam}\lambda}\frac{dT_{sam}}{T_{sam}}\right|^2+\left|\frac{hc}{kT_{ref}\lambda}\frac{dT_{ref}}{T_{ref}}\right|^2\right]^{\frac{1}{2}},\tag{3}$$

where error in the emittance of the reference material is assumed to be negligible.

At λ = 1 μm, where uncertainty becomes maximum,

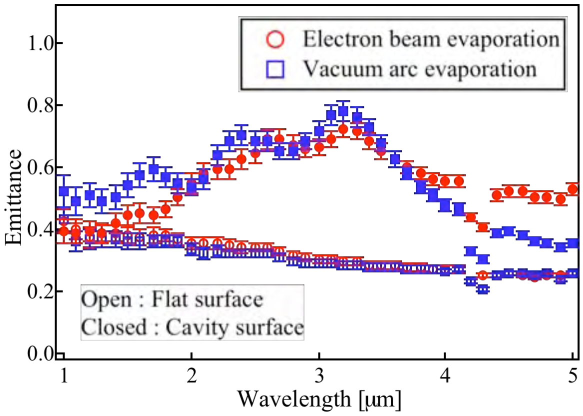

Fig. 7: Emittance spectra of 1.8 μm microcavities fabricated with EB and vacuum arc evaporation.

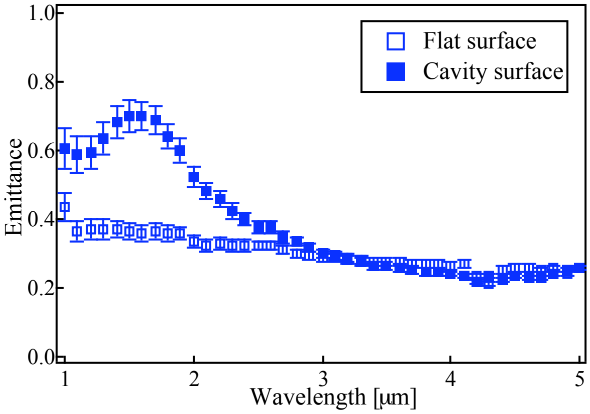

Fig. 8: Emittance spectra of 0.7 μm microcavities fabricated with vacuum arc evaporation.

the estimate of uncertainty interval at the 95 % coverage is within 10 % for $T_{sam} = T_{ref} = 900$ °C. Major source of the uncertainty is the sample temperature measurement.

RESULTS

Firstly, in order to validate the present measurement set-up, the radiation energy of Si substrate coated with blackbody paint was measured twice, and the emittance obtained is compared with the reference value. Figure 6 shows the experimental results. The reference value of 0.94 is within the uncertainty interval at almost all the wavelengths.

Figure 7 shows the emittance spectra of 1.8 μm microcavities obtained at about 800 ˚C. The highest emittance peaks of both microcavities with EB and vacuum arc evaporation appear at the designed value. The other emittance peaks of vacuum-arc-fabricated microcavities correspond well to the electromagnetic resonance modes (Eq. 1). In addition, its emittance is higher in the short wavelength region if compared with the EB-fabricated microcavities, while it reduced to the flat wall value in the long wavelength region. Therefore, smooth surface provided by vacuum arc evaporation should have better performance of the conversion efficiency.

Figure 8 shows the emittance spectra of 0.7 μm microcavities. The emittance near the wavlength of 1.5 μm is much increased, whereas the emittance at longer wavelengths remains unchanged.

When Ge PV cell, of which bandgap wavelength is 1.9 μm, is assumed, ideal energy conversion efficiency is estimated to be 6.1 % for blackbody at 900 °C. When the present microcavities are employed with appropriate cavity dimensions, the estimate of the efficiency is much improved to 13 %.

CONCLUSION

Metal-coated Si microcavities are fabricated through DRIE of Si substrates and physical vapor deposition of Ti. The effects of the surface roughness on the emittance spectra of microcavities are investigated. It is found that metal-coated Si microcavities exhibit a strong emittance peak at the wavelength of the resonant mode, which corresponds to the designed value. Effect of the surface roughness is examined by using different metal coating methods, and a large effect on the electromagnetic resonance modes is quantitatively shown. It is also shown that the energy conversion efficiency can be increased to 13 % with the present microcavities.

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