Power generation characteristics of Si PV cell under extremely high-intensity near-infrared light irradiation

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Abstract Power generation characteristics of a Si PV cell under extremely high optical power near-infrared irradiation were investigated for use in optical wireless power transmission. We used high power LED light sources with 750 nm, 850 nm and 940 nm wavelengths and a condensing optics to realize 10-sun level extremely high optical power irradiation in the measurements. More than 0.22 W electrical power was generated from a 1 cm square Si heterojunction PV cell under about 1 W/cm² optical power irradiation. This is more than 10 times the power generation density of conventional Si solar panels. Estimated power conversion efficiencies under 10-sun power level near-infrared irradiation exceeded 22.5%, which indicate a potential for high-power wireless transmission with Si PV cells using near-infrared light.

key words: Optical wireless power transmission, high optical power, near-infrared light, Si PV cell, power generation characteristics

Classification: Integrated optoelectronics (choose one from Table II)

1. Introduction

Optical wireless power transmission (OWPT) [1-13] is studying as an attractive method for supplying electric power to remote moving objects such as electric vehicles [12] or drones [13] wirelessly. Both require very high supplied power for maintaining the operation. Therefore, high power transmission as well as high power conversion efficiency is required for the photoelectric power conversion devices such as PV cells. Especially in optical wireless power transmission using laser beam [8], it is expected that the light receiving element will be irradiated with extremely strong intensity light, so it is important to investigate the photoelectric conversion characteristics under such an extreme condition. Widely used conventional silicon (Si) PV cells are known to exhibit high power conversion efficiency in near-infrared wavelength region around 1 μm [7]. Therefore, we decided to use Si PV cell as the light receiving element of OWPTs using near-infrared light beam.

In this paper, we report power generation characteristics for a Si PV cell when it is irradiated under extremely high intensity near-infrared light.

2. Experiment method

Since it shows excellent power generation characteristics even at high temperatures, we decided to use a heterojunction Si PV cell [14-17] as a photoelectric conversion element for the scheme. Figure 1 (a) shows a photo of the Si PV cell manufactured by Kaneka [17] used for the experiments. The size of the light receiving window area was 9.65 mm × 9.55 mm (active area was 0.922 cm²) and attached to a 23 mm square heatsink.

First, we investigated power generation characteristics under irradiating sunlight by using a solar simulator. From measured power generation V-I curves and with simple calculation, we can obtain the open circuit voltage (Voc), short circuit current (Isc), maximum output power (Pmax), power conversion efficiency (Eff) and fill factor (FF) for the cell. Table I shows the values under irradiating 1-sun and 2-sun levels (100 mW/cm² and 200 mW/cm², AM1.5) power density sunlight. In both cases, the power conversion efficiency was about 21.6%.

Next, the power generation characteristics of the PV cell under irradiating pseudo monochromatic near-infrared light were measured with various irradiation power levels of about 100, 300, 600, 800 and 1000 mW/cm² which correspond to 1-, 3-, 6-, 8- and 10-sun power levels under sunlight. We used 730 nm, 850 nm and 940 nm of three different wavelengths high-power LEDs with 2 cm square of light emitting area. In addition, a condensing optics made of pyramid shape inner mirror was attached to the LEDs for realizing measurements at high intensity as shown in Fig. 1 (b). Figure 1 (c) shows measured emission spectra of the LEDs as well as solar irradiation spectrum (AM1.5) [18].

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DOI: 10.1587/elex.19.20210476
Received November 08, 2021
Accepted January 06, 2022
Publicized January 14, 2022
3. Power generation characteristics of Si PV cell

Figure 2 shows the power generation V-I and V-P curves under irradiating five different optical power conditions measured with the three different wavelength LEDs. In order to eliminate the effect of the temperature rise of the PV cell during measurements, the measurements were performed quickly in 2 to 3 seconds. From the measured V-I curves with 730 nm, 850 nm and 940 nm LEDs, we can estimate values of $V_{oc}$, $I_{sc}$, $P_{max}$, Eff and FF, and summarized in Table II.

![Fig. 1. The photos of (a) the Si PV cell, (b) the high power LED light source and the light condenser, and (c) the spectral irradiance of 730 nm, 850 nm, 940 nm light and sunlight used in the experiment.](image)

| Irradiation power (mW/cm²) | $V_{oc}$ (V) | $I_{sc}$ (A) | $P_{max}$ (W) | Eff (%) | FF (%) |
|---------------------------|--------------|-------------|--------------|--------|-------|
| 100 (1-sun)               | 0.725        | 0.0371      | 0.0216       | 21.6   | 80.4  |
| 200 (2-sun)               | 0.738        | 0.0714      | 0.0432       | 21.6   | 81.9  |

![Table I. Power generation characteristics under sunlight.](image)
In Fig. 3, those values were plotted as a function of irradiation power [19]. From Fig. 3 (a), the values of $V_{oc}$ were almost same at the same irradiation power conditions for sunlight and three near-infrared wavelengths (730, 850 and 940 nm), and those were increasing as the irradiation power and saturated around 0.775 V. The tendency of almost no wavelength dependence were observed in $I_{sc}$ and $P_{max}$ as shown in Fig. 3 (b) and (c). The $I_{sc}$ and $P_{max}$ values increased linearly with the irradiation power for all wavelengths. The $P_{max}$ value reached about 0.23 W under 10-sun power irradiation level. We also estimated values of external quantum efficiency (EQE) for the three wavelengths. The EQE was gradually decreased as the wavelength became longer as 63.9%, 55.8% and 48.1% for 730, 850 and 940 nm wavelengths, respectively.

Above mentioned measurements were performed within 2 to 3 seconds light irradiation for avoiding effects of heating. However, for the practical application of OWPT, the effect of temperature rise is inevitable because the strong light will be continuously irradiated to PV cells. Therefore, for next step, we measured the temperature rise of the PV cell when irradiated with very strong light reached to 10-sun level (1 W/cm² power density) and investigated power generation characteristics under continuously irradiating condition.

We measured the heatsink temperature and power generation V-I curve for every half minute during 10 minutes from the irradiation under 1-sun and 2-sun power levels for sunlight, and 1-sun and 10-sun power levels for 730 nm, 850 nm and 940 nm LED lights continuous irradiation. The measured temperature, $V_{oc}$, $I_{sc}$, $P_{max}$, and $Eff$ values after 10 minutes irradiation are listed in Table III.

Figure 4 (a) shows the change in temperature over time. The cell temperature begins to rise with irradiation, and the temperature rise was higher in the order of 1) 730 nm, 2) 850 nm and 3) 940 nm at 10-sun power level, sunlight at 4) 2-sun and 5) 1-sun power level, 6) 730 nm, 7) 850 nm and 8) 940 nm at 1-sun power level. This indicates that light absorption coefficient is higher in the order of 1) 730 nm, 2) 850 nm and 3) 940 nm for near-infrared light, and absorption for sunlight is relatively higher than those near-infrared light [20, 21]. The temperature increased when irradiated at 10-sun power level ranged from about 15-21 degrees from room temperature of 25-26°C.

Figure 4 (b) shows the change in the $Eff$ values over time. In the case of 1-sun power level, the $Eff$ didn’t decrease much as time passed. In the case of 10-sun power level, although the $Eff$ gradually decreased due to the temperature rise over time [22-24], they still maintained high values over 21.5%. Although the $Eff$ of 940 nm was relatively low when there was no influence of temperature, under continuous irradiation condition, the $Eff$ of 940 nm was higher than that of 730 and 850 nm, and still maintaining over 21.7%.

Table II. Power generation characteristics under pseudo near-infrared light of 730 nm, 850 nm, 940 nm.

| Wavelength (nm) | Irradiation power (mW/cm²) | $V_{oc}$ (V) | $I_{sc}$ (A) | $P_{max}$ (W) | $Eff$ (%) | $FF$ (%) |
|----------------|---------------------------|-------------|-------------|--------------|-----------|----------|
| 109            | 0.725                     | 0.0410      | 0.0247      | 22.6         | 82.9      |
| 311            | 0.756                     | 0.117       | 0.0719      | 23.1         | 80.9      |
| 730            | 619                       | 0.769       | 0.234       | 0.142        | 23.0      | 79.1     |
|                | 814                       | 0.773       | 0.307       | 0.184        | 22.6      | 77.4     |
|                | 1009                      | 0.775       | 0.381       | 0.227        | 22.5      | 76.8     |
| 850            | 619                       | 0.756       | 0.120       | 0.0716       | 23.0      | 79.1     |
|                | 814                       | 0.772       | 0.317       | 0.185        | 22.7      | 75.5     |
|                | 1009                      | 0.774       | 0.390       | 0.226        | 22.4      | 75.0     |
| 940            | 619                       | 0.769       | 0.241       | 0.142        | 22.9      | 76.6     |
|                | 814                       | 0.773       | 0.317       | 0.185        | 22.7      | 75.5     |
|                | 1009                      | 0.774       | 0.390       | 0.226        | 22.4      | 74.9     |
The wavelength dependence can be explained that, since the light absorption of 940 nm LED is relatively lower, so that under high power irradiation, the cell temperature increase (about 15℃) was less than that of the case of 730 nm (about 21℃) and 850 nm (about 17℃). This also indicates the advantages of OWPT using near-infrared lights as light sources [25, 26].

Figure 5 (a) shows a plot of the $V_{oc}$ as a function of the cell temperature. At all wavelengths, the $V_{oc}$ decreased at the rate of 1.79 mV/℃. As the temperature rise, the intrinsic carrier density in the light absorption layer increase which resulted in excessive recombination current densities, and it may have led to a drop in the $V_{oc}$ [27-29].

**Fig. 3.** The effect of different wavelengths lights and irradiance conditions on the cell’s power generation performance measured under 1, 2 suns of sunlight, and 1, 3, 6, 8, 10 suns of monochromatic light with 730 nm, 850 nm, 940 nm wavelength: (a) $V_{oc}$ (b) $I_{sc}$ (c) $P_{max}$.

**Fig. 4.** The operating cell temperature, the effect of temperature on $Eff$ measured under 1, 2 suns of sunlight, and 1, 10 suns of monochromatic light with 730 nm, 850 nm, 940 nm wavelength for 10min irradiation: (a) Temperature (b) $Eff$.

**Table III.** Power generation characteristics after 10 minutes constant light irradiation.

| Type of incident light | Sunlight | Pseudo monochromatic near-infrared light |
|-----------------------|----------|-----------------------------------------|
| Wavelength (nm)       | 730      | 850                                     |
| Irradiation power (mW/cm²) | 100   | 109                                     |
| Temperature (℃)       | 28.5     | 27.1                                    |
| $V_{oc}$ (V)          | 0.718    | 0.723                                   |
| $I_{sc}$ (A)          | 0.0367   | 0.0419                                  |
| $P_{max}$ (W)         | 0.0214   | 0.0249                                  |
| $Eff$ (%)             | 21.4     | 22.5                                    |
Figure 5 (b) shows a plot of the $I_{sc}$ as a function of the cell temperature. As it can be seen that the $I_{sc}$ is almost independent on temperature. As the temperature increase, the band gap energy of materials that construct the light absorption layers will become smaller, which cause the increase of $I_{sc}$. $I_{sc}$ is rather affected by the intensity of the incident light. The same situation appears in Fig. 5 (c). The $FF$ is also almost independent on temperature. As the temperature increase, the photocarriers crossing a barrier layer which contacted to photo absorption layer is enhanced and resulted in an improved transport and, therefore, an increase in the $FF$ [30].

4. Conclusion

In summary, we reported power generation characteristics of a heterojunction Si PV cell for various irradiance conditions ranging from 1-, 3-, 6-, 8- and 10-sun power levels, by near-infrared light with three different wavelengths of 730 nm, 850 nm, 940 nm. From this study, we demonstrated that the Si PV cells have great potential to generate large electric power even under extremely high intensity (More than 0.22 W was generated from a 1 cm square cell under 1000 mW/cm² near-infrared light irradiation.) near-infrared light irradiation. Moreover, the operating cell temperature, as a major factor affecting conversion efficiency, was also investigated. The reduction in power conversion efficiency ($Eff$) was only 0.055%/°C. Therefore, we can make a conclusion that the practical application of optical wireless power transmission by using high intensity monochromatic near-infrared light is promising. We are currently underway an experiment to transmit higher power. A 0.5 W electric power generated by the same cell reported in this paper has been transmitted through 980 nm laser beam with 30-sun level high-intensity optical power over 1 meter distance indoor.

Acknowledgments

The authors thank to Dr. Nobuyuki Matsuda and Naomi Uchiyama for their useful technical discussions.

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