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Photovoltaic output parameters of a mono-crystalline silicon solar cell with non-uniform horizontal temperature distributions

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ABSTRACT

Temperature inhomogeneity occurs frequently in the application of photovoltaic devices. In the present study, the effect of nonuniform horizontal temperature distributions on the photovoltaic output parameters of a monocrystalline silicon solar cell including short-circuit current, open-circuit voltage, output power, etc. was investigated. A laser beam irradiated on the center of the cell surface was used to obtain nonuniform temperature distributions. The results show that the higher initial temperature region of the solar cell absorbs more heat energy and achieves higher temperature than the lower initial temperature region after exposure to the same sunlight. Meanwhile, the photovoltaic parameters vary with the temperature difference between the center and edge of the solar cell. The maximum output power decreases exponentially with the temperature difference. The output power under an external load resistance of 1 Ω is almost inversely proportional to the temperature difference. According to the experimental results, when the temperature difference between the center and edge of the solar cell changes from 0 K to 60 K, the open-circuit voltage, maximum output power, output current, and power under external load resistance of 1 Ω would decrease by 4.8%, 4.8%, 5.1%, and 9.8%, respectively. The photovoltaic efficiency decreases when the temperature distribution is nonuniform.

I. INTRODUCTION

Research on applications of solar energy has been promoted a lot recently. Specifically, for the performance of solar cells, it has received a lot of attention from researchers. Among the factors that affect the output of solar cells, temperature is the significant one and has a non-negligible effect on the photovoltaic parameters. Numerous studies have illustrated that the temperature is detrimental to the performance of monocrystalline silicon solar cells. In accordance with previous publications, photovoltaic parameters including short-circuit current, open-circuit voltage, maximum output power, fill factor, conversion efficiency, etc. are significant quality indicators of a solar cell.[1,2] It has been pointed out that the open-circuit voltage, maximum output power, fill factor, and conversion efficiency decrease with the temperature rise. On the contrary, short-circuit current increases slightly with the temperature rise.[3–8] The temperature rise has a negative effect on the output of the solar cell. However, it is inevitable because the solar cell cannot convert all the solar energy into electric power and 60%–70% of solar energy will be wasted in the form of heat dissipation in practice. As the temperature effect has become more and more significant to forecast the performance of solar cells, many researchers have conducted a lot of studies on this. Dupré *et al.*[9] discussed the temperature effects on the fundamental losses in photovoltaic conversion. The additional losses like nonradiative recombination were illustrated in this literature. Furthermore, they explained the temperature dependence of photovoltaic conversion under real conditions and presented the transformation from unused energy to thermal energy. Singh and Ravindra[10] investigated the temperature effects on the performance of solar cells in the temperature range of 273–523 K theoretically. The connection between the bandgap and temperature was presented in their study. In addition, they calculated the temperature coefficients of the short-circuit current, open-circuit voltage, fill factor, and photovoltaic efficiency. Zhao *et al.*[11] illustrated the temperature dependences of semiconductor material properties including the energy bandgap, electron and hole mobilities, effective masses, electron affinity and density of states to explore the mechanism of the temperature dependence of performance of solar cells. They analyzed the effects of operation temperature on the efficiencies of different solar cell materials. Besides the theoretical analysis, many researchers paid attention to the experimental investigations on the temperature coefficients of photovoltaic parameters. Hossain *et al.*[12] investigated a reliable steady-state estimation model of solar cell temperature, which can calculate the real conditions of the solar cell more accurately than previous research. Kinsey *et al.*[13] studied the performance of multijunction solar cells. They measured the temperature coefficients of a three-junction cell. Peharz *et al.*[14] investigated the effects of temperature on the I-V characteristics of concentrator photovoltaic modules equipped with III–V triple-junction solar cells. They explored the temperature coefficients of the open-circuit voltage and fill factor and found that the variation trend of open-circuit voltage of the concentrator photovoltaic modules was about equal to the individual triple-junction solar cells. Research on the temperature dependence of solar cell performance has been abundant, whereas most of the studies assume that the temperature is uniform in solar cells. In fact, the temperature distributions of solar cells are always nonuniform in practical applications. Lu *et al.*[15] pointed out that even the temperature of the front surface was the same as that of the back surface, and the temperature distributions inside the cell were inhomogeneous. They studied the effects of environmental temperature and the temperature difference between the front and back surfaces on the photovoltaic output parameters, respectively. Li[16] introduced the effect of nonuniform temperature on solar cells and presented the cell parameter analysis at nonuniform temperature of the photovoltaic system simply. Domenech-Garret[17] investigated the performance of solar cells with combined profiles of nonuniform temperature and radiation through theoretical simulation. Xing *et al.*[18] explored thermal and electrical performances of silicon vertical multijunction solar cells under nonuniform illumination by using the finite element method and SPICE software, respectively. Besides simulation studies, Andreev *et al.*[19] indicated the influences of nonuniform irradiation on temperature coefficients in the concentrating system. Baig *et al.*[20] presented a review on nonuniform illumination in concentrating solar cells, including the causes of nonuniformity and measures to reduce the effect of nonuniformity.

As many studies have indicated in the past few years, the nonuniform temperature distribution has a significant effect on the performance of solar cells. However, most of the studies investigated the effect of nonuniform illumination by numerical simulation in the concentrating system. In practical situations, the operating temperature of the solar cell can be nonuniform due to the influence of partial shadows, mismatched illumination angles, etc. even under a uniform illumination. As a result, the influence of nonuniform temperature distribution on the performance of solar cells needs more considerations. The variation of photovoltaic parameters of a single crystalline silicon solar cell under nonuniform temperature distribution but uniform illumination has been explored in this study to investigate the mechanism of the nonuniform temperature distribution effect on the photovoltaic parameters. An infrared laser with alterable output energy is used to establish different temperature distributions on the back surface of the solar cell without altering other parameters. The solar cell is placed in a vacuum environment in order to avoid heat convection. The variation of photovoltaic parameters including short-circuit current, open-circuit voltage, and output power is analyzed under different temperature distributions. The behavior and effect of nonuniform temperature distribution in the photoelectric conversion have been investigated in this work. In addition, the solar cell was connected with a 1 Ω standard resistor and an ampere meter of low resistance in series in order to imitate a real working state. The variation of output power of solar cells in different nonuniform temperature distributions has been studied in this situation. The effect of nonuniform temperature on the output power of a solar cell was discussed in this study. This work aims to explore the mechanism of the photoelectric conversion process under nonuniform temperature conditions. It is devoted to providing a reference for predicting the performance of the solar cell in various environments.

II. EXPERIMENTAL SETUP

The schematic of the experimental device is shown in Fig. 1 (for the image of the experimental device, see Appendix A). A solar simulator was employed to provide uniform sunlight. The solar irradiance was measured using a solar power meter. A vacuum thermostat was used to provide a vacuum environment by cooperating with a vacuum pump and ensure that the solar cell can work in a steady situation to eliminate the influence of heat convection on the temperature of solar cells from air. A monocrystalline silicon solar cell wafer of (30×30) mm^2 area and (200 ± 20) μm thickness, used as an experimental subject, was placed on the constant temperature platform which was controlled by a vacuum thermostat with a ± 0.1 K temperature accuracy. The temperature distribution of the solar cell was measured using five thermocouples distributed on the back surface of the solar cell equidistantly with a ± 0.5 K accuracy. A laser device that emits 1064 nm wavelength and 500 μm diameter infrared light on the center of the back surface of the solar cell from a 45° angle was used to establish different nonuniform temperature distributions by altering the output power of the laser. As the external quantity efficiency of 1064 nm wavelength is small enough, this project can avoid the photoelectric conversion caused by the laser light when the laser emits on the back surface of the solar cell.

Therefore, the laser light can provide different temperature distributions without changing any other parameters. The level of the nonuniform temperature condition is reflected by the temperature difference between the center and the edge region of the back surface. The photovoltaic parameters under different nonuniform distributions were measured using a Keithley 2450 meter. To investigate the effect of nonuniform temperature on the practical performance of solar cells, the solar cell was connected in series with a 1 Ω standard resistor and an ampere meter of low resistance in order to obtain high output power and imitate a real working station. In this work, the light intensity and the initial temperature were set to 1000 W/m^2 and 300 K, respectively. The level of nonuniform temperature distribution represented by the temperature difference between the center and edge region of the solar cell was changed from about 0 K to 60 K by altering the laser heat energy from 0.25 W to 2.02 W. The effect of nonuniform temperature distribution on the solar cell was studied by comparing the experimental results under various degrees of nonuniform temperature distribution conditions with the standard condition.

III. RESULTS AND DISCUSSION

A. Temperature distribution

It is obvious that the temperature of solar cells can increase a lot when it is exposed to illumination.[21] Figure 2 depicts the temperature

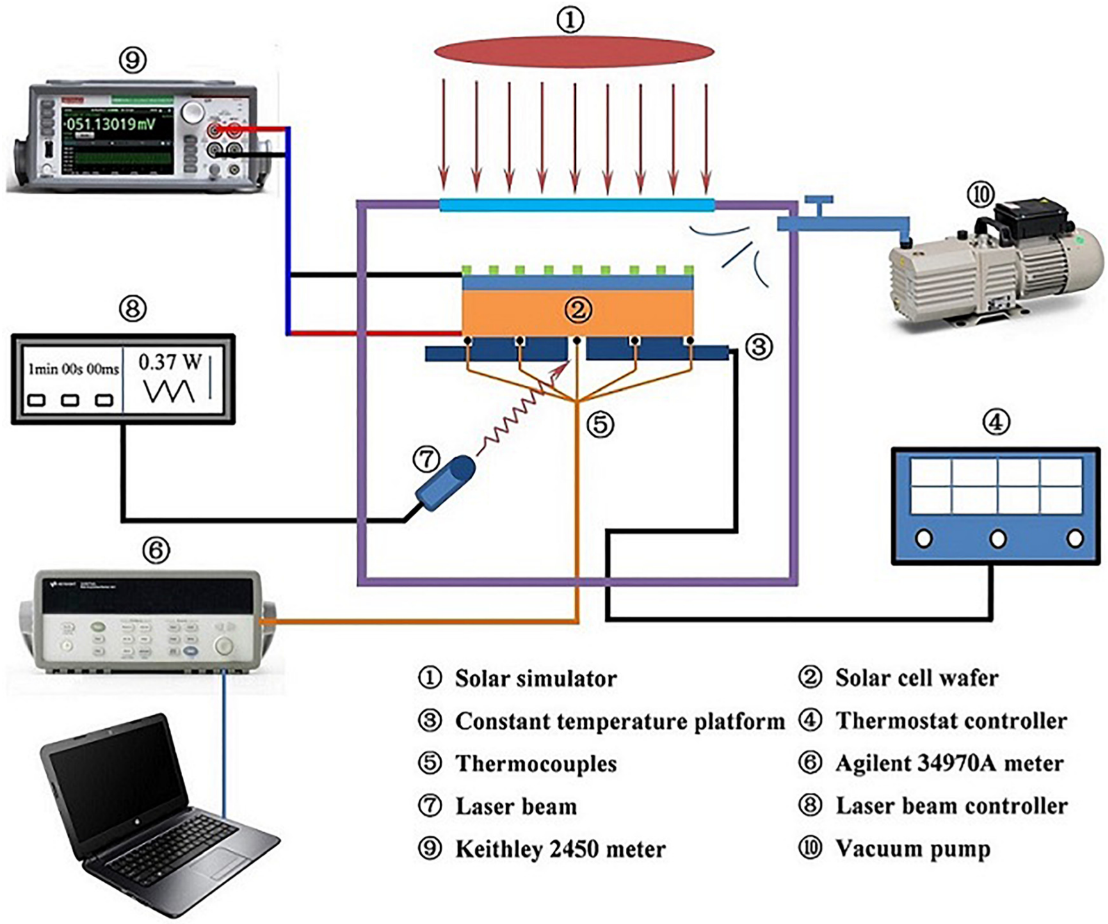

FIG. 1. Schematic of the experimental device.

variation of the solar cell back surface, which was measured using five thermocouples under different conditions. As shown in Fig. 2, the red line obtained by linear fitting represents the initial state of the solar cell in the vacuum thermostat. The temperature distribution is uniform before exposure to the laser. The temperature increases by 8.09 K uniformly, which is shown by the line named standard sunlight, when the solar cell is exposed to standard sunlight. The existing literature has shown that solar energy cannot be converted into power entirely in the process of photoelectric conversion.[22] After exposure to the standard sunlight, solar cells will absorb a large portion of solar energy and convert part of it into heat. This part of heat can store in the interior of the solar cell and become a significant portion of heat generation. So the temperature will increase until the heat transfer equals heat generation.[23]

A heating laser beam was used in this study to explore the effect of nonuniform temperature distribution on the performance of the solar cell. Before exposure to the light, the center area of the solar cell back surface was heated by a laser beam first. The variation of solar cell temperature at a laser energy of 0.37 W is shown by the green line in Fig. 2. This line is derived from linear fitting according to the general solution form of two-dimensional heat

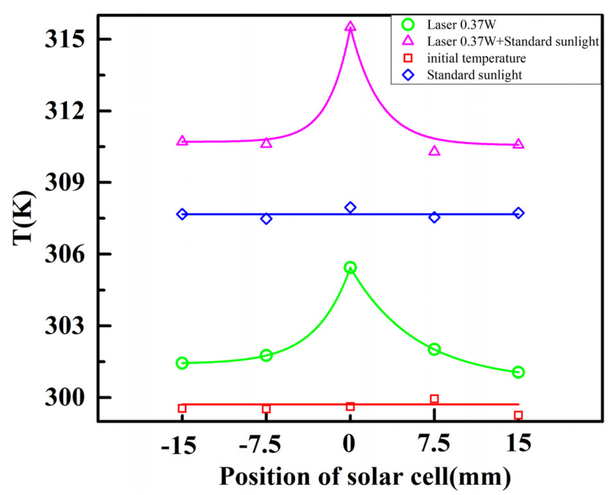

FIG. 2. Variations of temperature distributions of the solar cell under different conditions.

conduction. As shown in Fig. 2, all the temperatures measured using five thermocouples will increase after being exposed to the laser light.

Furthermore, the temperature of the center region increases more than that of the else regions. The highest and lowest temperatures are about 305.4 K and 301.1 K, respectively. After the nonuniform temperature distribution has been established, the solar cell is heated by the simulated standard sunlight. The temperature distribution is shown by the fitted lines marked as laser 0.37 W and standard sunlight in Fig. 2. However, the temperature rise of different regions is not uniform. The highest temperature of the center region increases by 10.1 K from 305.4 K to 315.5 K. The lowest temperature of the edge region increases by 9.5 K from 301.1 K to 310.6 K. The value of the temperature rise of the center region is higher than that of other regions because it has higher temperature. The transient variation of temperature was taken into account besides the results in the steady state to study the details of the temperature rise. Figure 3 shows that the rates of temperature rise change with time at different initial temperatures when the solar cell is exposed to the same light intensity. It can be seen from Fig. 3 that the rate of temperature rise increases with initial temperature. The rates of temperature rise are almost the same at the beginning under various initial temperature conditions. Subsequently, they can reach different values. The value of the rate of temperature rise will be larger under higher initial temperature situations. Therefore, the center region whose initial temperature is higher than that of other areas can absorb more heat energy after exposure to the same light intensity. Many literature studies show that the surface light absorption of the solar cell increases with the temperature rise. Many researchers indicate that the bandgap energy is inversely proportional to the temperature.[24] Consequently, the bandgap energy of the center region is lower than that of other regions due to higher initial temperature. Only the photon whose energy exceeds bandgap energy can cause the photoelectric effect. As a result, more photons are converted into electron and hole pairs in the center region of the solar cell. The concentration of electron hole pairs will increase for this

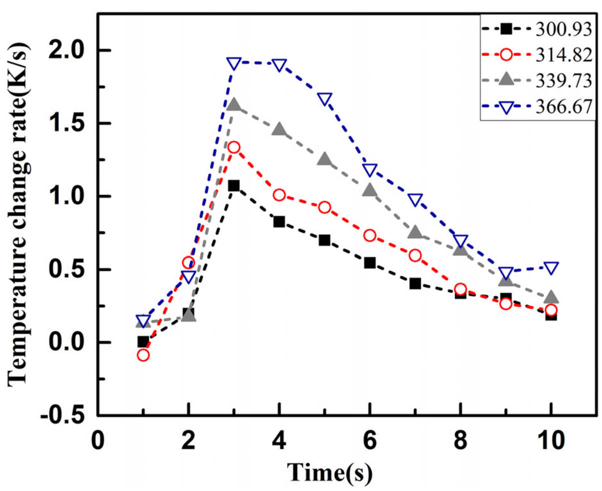

FIG. 3. Rate of temperature change with time at different initial temperatures after exposure to sunlight.

reason. The probability of collisions between electrons and holes becomes high due to the motivation from high temperature. Therefore, the recombination process is enhanced.[25] More heat energy is generated under this condition. In addition, the photoelectric current of the center region is higher than that of other regions because of the higher concentration of electron and hole pairs. The joule heat generated by the center region becomes higher than that of other regions. Generally, the photovoltaic efficiency is inversely proportional to the temperature. So less solar energy will be converted into power if temperature will increase. On the contrary, more solar energy can be converted into heat energy. As a result, the temperature of the center region increases a little more than that of the other regions.

B. Photovoltaic parameters

Short-circuit current represents the ability to generate electron hole pairs in solar cells. Figure 4(a) shows the variation of short-circuit current at different levels of nonuniform temperature conditions. It is shown that the short-circuit current varies slightly with the temperature difference. Short-circuit current, which depends on the concentration of electron and hole pairs, is influenced by the association of generation and recombination. As the bandgap energy is inversely proportional to the temperature, the bandgap of the high temperature region of the solar cell narrows with the temperature rise. Then, more photons are absorbed and converted into electron and hole pairs.[26] Moreover, the high temperature region occupies a small part of the solar cell according to the temperature distribution. Therefore, the concentration of electron and hole pairs would change little. Thus, the short-circuit current is nearly constant.

Figure 4(b) shows the variation of open-circuit voltage at different levels of nonuniform temperature conditions. The open-circuit voltage is inversely proportional to the temperature difference. When the temperature difference between the center and the edge region of the solar cell changes from 0 K to 60 K, the open-circuit voltage decreases by about 4.8%. In fact, the open-circuit voltage of the solar cell is a good indicator of the balance between the overall recombination rate of carriers and the photogeneration rate. As mentioned above, the generation process is slightly enhanced by increasing the temperature difference. However, the recombination is enhanced by high temperature because the vibration of electrons and holes is strengthened in the high temperature situation.[27] In addition, the free carriers separated from electron-hole pairs cannot be transported to the electrode efficiently under the open-circuit condition. Therefore, this can result in violent recombination. The balance is broken, and the open-circuit of the high temperature region will decrease. The other regions will make up for the changing voltage. As a result, the open-circuit voltage decreases on the whole.

The maximum output power is the output power of a solar cell which works under optimized conditions. It represents the optimal photoelectric conversion ability of the solar cell. The maximum output power is influenced by temperature. The maximum output power similar to the open-circuit voltage decreases with the temperature rise. When the middle area of the solar cell reaches higher temperature, the maximum output power will decrease accordingly. Figure 5 presents the relationship between the maximum output power and the temperature difference. The maximum output power decreases logarithmically with the temperature difference approximately. When the

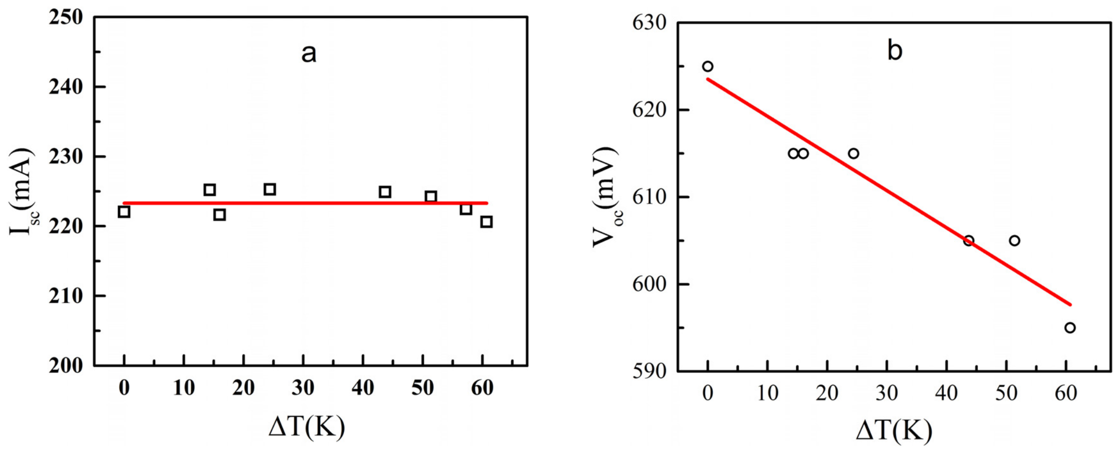

FIG. 4. Variation of short-circuit current and open-circuit voltage with the temperature difference.

temperature difference changes from 0 K to 60 K, the maximum output power decreases by about 4.8%.

The output power under an external load of a standard resistance was measured to explore the working state of the solar cell under practical conditions. As shown in Fig. 6(a), the output current under an external load resistance of 1 Ω varies with the temperature difference. The output current is inversely proportional to the temperature difference linearly. When the temperature difference changes from 0 K to 60 K, the output current reduces by 5.1% approximately. Figure 6(b) presents the variation of output power under an external load resistance of 1 Ω. The output power reduces by 9.8% when the temperature difference changes from 0 K to 60 K. Many studies have indicated that the output power decreases with the temperature rise because the carrier lifetime can be reduced due to the temperature rise.[28] The relation between the nonuniform temperature and the output power is complicated. As mentioned in Sec. III A, the bandgap of the higher temperature region of the solar cell is narrower than that of the other regions since the bandgap energy is inversely proportional to the temperature. Therefore, the higher temperature region can absorb more photons and generate more electron and hole pairs. The free carrier concentration of the higher temperature region becomes larger than that of the other regions. So the recombination process is strengthened in the interior of the higher temperature region of the solar cell. Meanwhile, the free carriers will diffuse from the higher temperature region to other regions forced by the different concentrations because of the different quantity of free carriers. The high temperature region can get a higher carrier concentration under nonuniform temperature distribution conditions. A part of electron and hole pairs is transported to the other regions because of the different concentration. As a result, this process weakens the carrier transportation. Many studies have indicated that the carrier mobility increases with the temperature rise.[29] The collision between electrons and holes occurs more frequently. Then, the recombination process can be enhanced further. In addition, the series resistance between the electrode and the silicon wafer increases with the temperature rise. More power is consumed on the series resistance in the form of Joule heat. Therefore, the ability of carrier transportation cuts down. Consequently, the average free carrier lifetime cuts down due to the nonuniform temperature condition. The output power decreases more violently under nonuniform temperature distribution compared to the uniform temperature distribution.

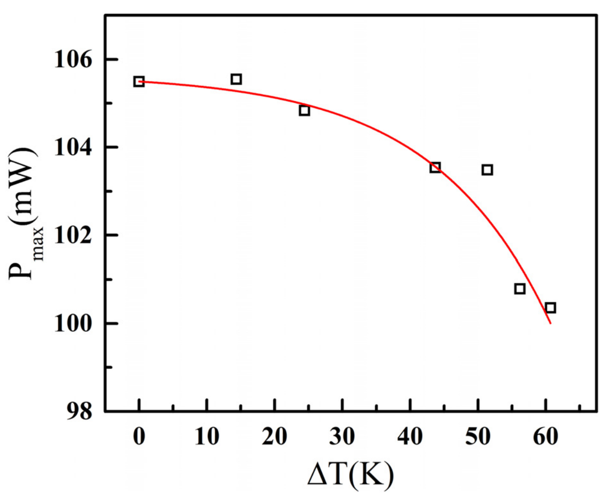

FIG. 5. Variation of the maximum output power with the temperature difference.

IV. CONCLUSION

In the present work, the effects of nonuniform cell temperature on both the temperature distribution and the photovoltaic parameters have been investigated. The temperature of different regions in the tested monocrystalline solar cell increases differently because of different initial temperatures. The higher initial temperature region of the solar cell absorbs more heat energy and achieves higher final temperature after exposure to standard sunlight. The surface absorption of the solar cell increases with temperature, while the bandgap energy decreases with temperature. Therefore, more photons can be converted into electron and hole pairs in the higher temperature region. The recombination can be enhanced due to the rise of carrier densities.

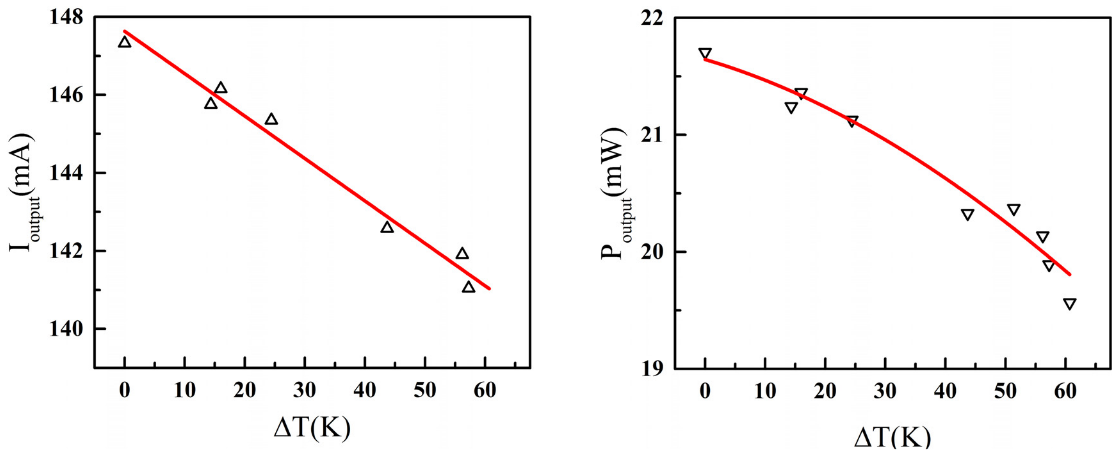

FIG. 6. Variation of the output current and power with the temperature difference under an external load.

The nonuniform temperature distribution influences the photovoltaic effect negatively. The results show that the short-circuit current changes slightly. However, the open-circuit voltage and maximum output power change a lot. When the temperature difference between the center and edge region of the solar cell changes from 0 K to 60 K, the open-circuit voltage, maximum output power, output current, and power with an external load resistance of 1 Ω decrease by 4.8%, 4.8%, 5.1%, and 9.8%, respectively. The higher temperature region achieves a lower carrier concentration because of the enhanced recombination and lower carrier mobility. Then, the photovoltaic efficiency of the solar cell decreases because of the nonuniform temperature distribution.

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APPENDIX A: THE IMAGE OF EXPERIMENTAL DEVICES

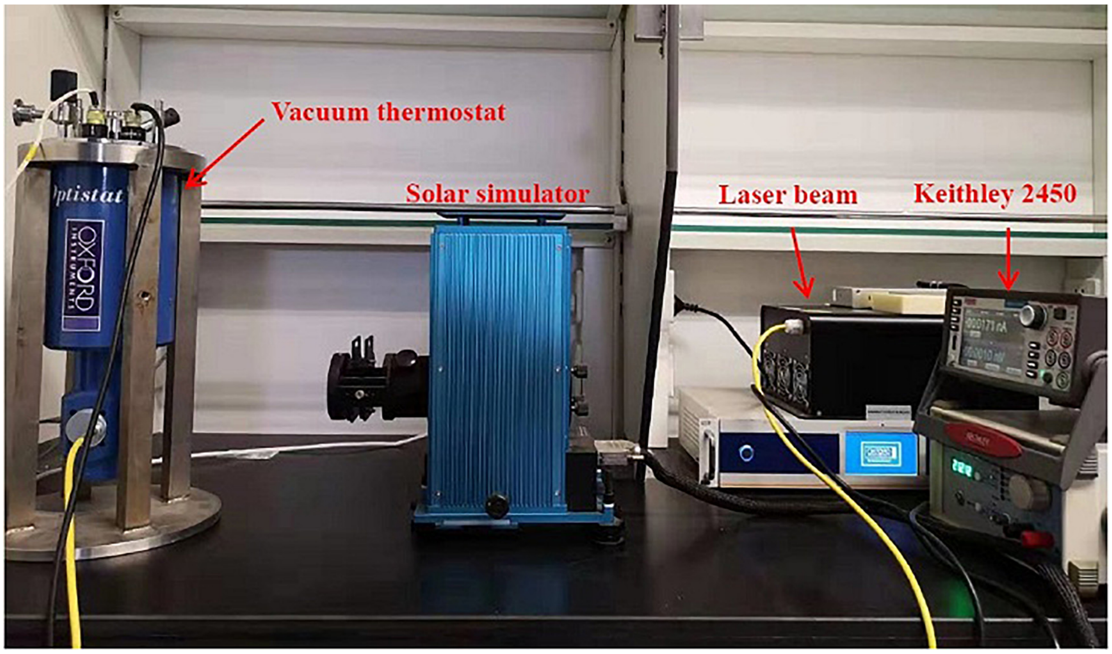

FIG. 7. The image of experimental devices.

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