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Temperature impact on parameters of $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ PV cell under laser irradiation condition

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ABSTRACT

The parameters of $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ PV cell applied in laser wireless power transmission (LWPT) system dependence on temperature was investigated at a temperature range of 5-90°C under 100mW/cm$^2$ laser intensity with 1070nm wavelength. The pollination algorithm method was used to extract parameters, viz., photocurrent, series and shunt resistance, reverse saturation current, and ideality factor from the I-V curves at each temperature point. The results show that the short circuit current decrease exponentially with temperature increasing, which is obviously different from the condition with solar irradiation. As temperature increases, the conversion efficiency and the open circuit voltage decreases linearly at the rate of 0.095%/°C and 1.89mV/°C, respectively. In addition, the dependence of series and shunt resistance, ideality factor, and fill factor on temperature was also analyzed. This research gives us a new understanding of PV cells under laser irradiation condition, also provides a direction for manufacturing the cells used in LWPT system.

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Much literature about the parameters dependence on temperature under solar irradiation condition has been published. To the best of our knowledge, however, there is no report has been published concerning the condition with laser irradiation. In this study, we investigated the temperature dependence of the performance and cell parameters of $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ PV cell under 1070nm fiber laser irradiation condition. As Mason has reported that the fiber laser and the custom-made InGaAs PV cells are the most promising chooses in LWPT system. The results in this paper are quite different from the condition with solar irradiation. It offers a reference for the production of PV cells used in LWPT, and can predict the performance of PV cells under different temperatures.

Parameters for the performance evaluation of a PV cell are extracted from the current-voltage (I-V) characteristics. Among the mathematical models available to describe these I-V curves, the most widely used is the single-diode model, due to its simplicity and accurate results. The equation describing this model can be
written as:  

\[ I = I_{ph} - I_0 \left( \exp \left( \frac{q(V + IR_s)}{nkT} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}}, \]  

(1)

where, \( I \) and \( V \) are the current and voltage of the module terminal, \( R_s \) and \( R_{sh} \) are the series and shunt resistance, \( n \) is the diode ideality factor, \( I_{ph} \) and \( I_0 \) are the photocurrent and reverse saturation current, \( q \), \( k \) and \( T \) are the elementary charge, Boltzmann constant, and temperature, respectively. In our previous work, we validated the applicability and accuracy of the pollination algorithm method to extract parameters of PV cells under laser irradiation condition, and we use the same method in this paper.

The PV cell used in this experiment was a single-junction InGaAs, the same with our previous work. The PV cell was mounted on a thermostat within \( \pm 0.2^\circ \text{C} \). The illuminated I-V characteristics were obtained by a digital source meter (Keithley model 2450) at temperature varying from 5°C to 90°C, and used to extract the diode parameters (i.e. \( I_{ph} \), \( I_0 \), \( n \), \( R_s \), and \( R_{sh} \)) of PV cell by the pollination algorithm method. For all measurements presented in this work, the irradiation intensity of the laser was 100mW/cm². Finally, the diode parameters obtained by the algorithm were used to calculate the I-V curves by the Newton method.

Ten groups of I-V curves of the PV cell measured at various values of temperature (5, 10, 20, 30, 40, 50, 60, 70, 80, and 90°C) are shown in Fig. 1. The symbols and lines in the inset are the experimental and calculated results, respectively. (The temperature value of 30°C is chosen only as an example.) It is obvious that the calculated curves match fairly well with the experimental results. The objective function (root-mean-square error, RMSE) of all calculated curves in the pollination algorithm is less than \( 1.23 \times 10^{-4} \).

The behaviors of open circuit voltage and short circuit current with increasing temperature, including the best fit are shown in Fig. 2. As we can see, the value of \( V_{oc} \) decreases linearly with the increase of \( T \), with a changing rate (\( dV_{oc}/dT \)) of 1.89mV/°C. It is different from that under solar irradiation, due to the temperature coefficient of bandgap is different for different materials. In general, the bandgap of a semiconductor determines the value of the open circuit voltage of a PV cell, and it decreases with increasing temperature. Therefore, the open circuit voltage exhibits a strong dependence on temperature.

The short circuit current approximates exponential decline in a small range with the increase of temperature. In the range of 5-90°C, the relative change of the short circuit current is 2.7%. This result is totally different from the condition with solar irradiation. Under solar irradiation condition, the short circuit current shows a slight increase with temperature, that for the bandgap reduces with increasing temperature and more photons with lower energy can generate carries. While in our experiment, there is no photons with lower energy to be absorbed. At high temperature, the radiative emission increases, so as the recombination rate, this is attribute to the augmentation of the equilibrium carrier concentration. Due to the above reasons, the short circuit current decreases with increasing temperature, and, as we know, this is not mentioned in the previous literature.

The temperature dependence of the conversion efficiency and the fill factor are shown in Fig. 3. With temperature increasing, the efficiency drops linearly with a rate of 0.095%/°C, and the decreasing rate of the fill factor rises slightly. The efficiency of the PV cell can be expressed as

\[ \eta = \frac{I_{sc}V_{oc}FF}{P_{las}}, \]  

(2)

where \( P_{las} \) is laser intensity. Therefore the decrease in \( \eta \) with temperature is due to the decrease of \( V_{oc}, I_{sc}, \) and FF with increasing temperature.

The changing trend of the photocurrent of the PV cell with temperature is almost the same with the short circuit current, so the plot of \( I_{ph} \) is not given. Other parameters dependence on temperature are shown in Figs. 4 and 5. It can be noted that the series and shunt resistance decrease with temperature, and the decreasing rate of series resistance reduces obviously. The value of reverse saturation current increases exponentially with temperature, and the ideality factor remains almost constant.

Series resistance is a parasitic, power consuming parameter. It reduces the maximum achievable output power, and hence softens...
the I-V characteristics of a PV cell, which means decay in the fill factor.\textsuperscript{17,27} We all know that series resistance accounts for the ohmic losses due to the sum of contact resistance to the front and back, resistance of the bulk and the sheet resistance of the active layer. With temperature increasing, the resistance of the latter two factors decreases. So the change of the trend is first exponentially and then linearly,\textsuperscript{15} as shown in Fig. 4. Therefore, the reduction rate of series resistance drops with the increase of temperature.

Shunt resistance represents the current leakage of a PV cell, and it is generally associated with localized defect regions, which have a larger concentration of traps.\textsuperscript{17,28} These traps act as sinks for the majority carriers or the photo-generated minority carriers. As the temperature rises, more traps are depopulated (by charge carriers), resulting in an increase of the shunt current, hence, the decrease of $R_{sh}$.\textsuperscript{14,29}

The ideality factor reflects the carrier recombination in the quasi-neutral base and space charge dominated diode junction,\textsuperscript{30} generally varying from 1 to 2, and is also affected by the PV cell fabrication process.\textsuperscript{17,19} The decrease of the surface recombination and the resistance of the active layer leads to the decrease of the ideality factor with increasing temperature. While the increase of carrier recombination in the bulk promotes the increase of the ideality factor with increasing temperature.\textsuperscript{17,21,35} The ideality factor remains almost constant attribute to the above reasons.

The value of reverse saturation current increases exponentially with temperature, as shown in Fig. 5. It is the most affected parameter with a mean exponential increase of 7862.9%. The reverse saturation current corresponds to recombination in neutral regions, and increases with temperature because of the increase in the leakage or recombination carries.\textsuperscript{26,27,29,30} Therefore the increase of reverse saturation current with increasing temperature leads to the decrease of shunt resistance and hence the decline of open circuit voltage.

In summary, we chose the most suitable type of laser (fiber laser) and a better option of PV cell (In$_{0.3}$Ga$_{0.7}$As) used in LWPT to investigate the dependence of performance parameters and diode parameters on temperature. The open circuit voltage, the short circuit current, and the fill factor all decrease with increasing temperature. The exponential increase of reverse saturation current with increasing temperature is the critical factor affecting the efficiency of a PV cell. So, the performance of a PV cell deteriorate with the increase of temperature under laser irradiation condition. Above all, seriously controlling the operating temperature of the PV cell or producing the temperature-insensitive PV cell by reducing the sensitivity of the reverse saturation current is the significant way for the LWPT system development.

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