Experimental Investigations of Laser Intensity and Temperature Dependence of Single Crystal Silicon Photovoltaic Cell Parameters

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Abstract Photovoltaic cell performance determined by its parameters is of vital importance for laser wireless power transmission system. The output characteristics of single crystal silicon photovoltaic cell illuminated by diode laser operating at 940 nm are investigated. The relationship between output characteristics and two factors, i.e. laser intensity and temperature, are studied. The results indicate that with the increasing of laser intensity, short-circuit current increases linearly in low intensity levels and then begins to saturate. Both open-circuit voltage and efficiency has a maximum value with increasing laser intensity. The experimental maximum efficiency of photovoltaic cell at 293 K is 29.49%. In the range of 283 K~308 K, short-circuit current is independent of temperature in low intensity levels and decreases linearly in high intensity levels. Open-circuit voltage and efficiency decrease linearly with increasing temperature. However, their temperature coefficients vary with the variation in laser intensity. The relationship between series resistance and efficiency is also simulated. It shows that small series resistance and the reduction of recombination for photovoltaic cell are essential for efficient energy conversion under high intensity laser illumination.

Key words laser optics; output characteristics; experimental research; single crystal silicon photovoltaic cell; wireless power transmission

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激光辐照单晶硅光伏电池输出特性的实验研究

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摘要 光伏电池性能对激光无线能量传输系统设计有重要影响。采用940 nm激光辐照单晶硅光伏电池,研究了光伏电池输出特性随激光强度和电池温度的变化规律。研究结果表明,短路电流随激光功率增加呈现线性增加后饱和的趋势。开路电压和效率与激光功率的关系则呈单峰特性。实验测得光伏电池在293 K时最大效率为29.49%。在283 K~308 K范围内,激光功率较低时,短路电流受温度影响较小,基本保持不变。激光功率较大时,短路电流随温度升高而线性下降。开路电压和效率则随温度升高而线性下降,但下降速率随激光强度的变化而变化。同时仿真了光伏电池效率与串联电阻的关系。结果表明,在强激光辐照下,减小串联电阻,降低复合电流的大小是提高单晶硅光伏电池效率的两个重要方面。

关键词 激光光学; 输出特性; 实验研究; 单晶硅光伏电池; 无线能量传输

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1 Introduction

Laser wireless power transmission is a process by which electricity can be sent from the power source to a load, without

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use of wires. Actually, laser beam is the substitute for wires. This is ideal in applications where either an instantaneous amount or a continuous delivery of energy is needed, however, the conventional power supply approach is inconvenient, expensive, hazardous or impossible[1], e.g. space probe, remote unattended sensors. Photovoltaic system depending on sunlight has been used to generate electricity in isolated site[2]. While laser wireless power transmission system has extra advantages, laser is characterized with high energy density and small divergence, which allows a large amount of energy and a long distance transmission. So it can be beneficial for applications where a small receiver is needed.

Photovoltaic cell performance determined by its parameters, viz., short-circuit current, open-circuit voltage, fill factor and efficiency, has a strong impact on the whole system[3]. Meanwhile, photovoltaic cell parameters strongly depend on various factors such as laser intensity and temperature. Therefore, an accurate knowledge of interaction between such factors and photovoltaic cell parameters is of vital importance for a high efficient laser wireless power transmission system. Single crystal silicon photovoltaic cell is widely used for its low cost[4]. And this also provides a chance for laser wireless power transmission. Some researches has been conducted[5], but a comprehensive research on laser intensity and temperature dependence of single crystal silicon photovoltaic cell parameters, which may be very important[6], is not acquired. In this work, experiment has been carried on to investigate laser intensity and temperature dependence of parameters of single crystal silicon photovoltaic cell.

2 Theoretical basis

The $I-V$ characteristics of a silicon photovoltaic cell are widely described based on one diode model as given in Eq.(1)[7]:

$$I = I_{\mathrm{ph}} - I_0\{\exp[q(V + R_{\mathrm{s}}I)/nkT] - 1\} - (V + R_{\mathrm{s}}I)/R_{\mathrm{sh}}\ , \tag{1}$$

Where I_{ph} is photo-generated current, I_0 is reverse saturation current, R_{s} is parasitic series resistance, R_{sh} is parasitic shunt resistance, T is temperature, q is electron charge, n is ideality factor and k is Boltzmann constant.

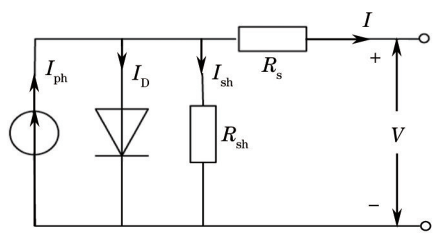

Fig.1 Equivalent circuit of photovoltaic cell

All kinds of photovoltaic cells have a specific peak response to monochromatic illumination. For silicon photovoltaic cell, the peak response wavelength is approximate 950 nm. The response to monochromatic illumination is due to photon energy and band gap of photovoltaic cell. For wavelength shorter than the peak response wavelength, the response decreases roughly linearly. And for wavelength longer than the peak response wavelength, the response decreases to zero rapidly. The cutoff wavelength is given in formula(2)[8]:

$$\lambda_c = hc/qE_g\ , \tag{2}$$

Where λ_c is cutoff wavelength, h is Plank constant, c is speed of light in vacuum, E_g is bad gap of photovoltaic cell. Response to cutoff wavelength of photovoltaic cell is zero. Thus, a laser wavelength near the peak response wavelength is important for efficient power transmission. As is shown in formula (3), the photo-generated current depends on illumination intensity and performance of photovoltaic cell[9].

$$I_{\mathrm{ph}} = qQE(E)b_s(E)\ , \tag{3}$$

Where $QE(E)$ is external quantum efficiency, $b_s(E)$ is illumination intensity. For monochromatic light, each photon has the equal energy which is shown in formula(4):

$$E_s = h\nu = q(1240/\lambda)\ , \tag{4}$$

Where E_s is photon energy, ν is frequency of monochromatic light, λ is wavelength of monochromatic light. Thus, illumination intensity can be acquired based on laser power P as follows:

$$b_s = P/E_s . \tag{5}$$

Quantum efficiency is a function of light wavelength. For monochromatic light, quantum efficiency is a constant. Substituting formules (4) and (5) in formula (3) yields:

$$I_{\rm ph} = QE \cdot P(\lambda/1240) . \tag{6}$$

Study shows that increasing of recombination current in depletion region under high injection conditions as follows[10]:

$$I_{\rm recom} = I_{02}[\exp(qV_d/2kT) - 1] , \tag{7}$$

Where $I_{\rm recom}$ is recombination current in depletion region, I_{02} is the dark saturation current, $V_d = V + IR_s$.

A simple empirical relation for I_0 is shown in formula (8)[3]:

$$I_0 = A \exp[-qE_g(T)/(kT)] , \tag{8}$$

Where, $A = 1.5\times10^8$ mA/cm^{-2} , $E_g(T)$ is band gap of semiconductor at temperature T . Temperature dependence of the band gap in semiconductor can be described as[11]:

$$E_g(T) = E_g(0) - \alpha T^2/(T + \beta) , \tag{9}$$

Where $E_g(0)$ is the value of band gap at $T \approx 0$ K , α and β are constants. Their values for several semiconductor materials are shown in Table 1[11].

Table 1 Band gap parameters for several semiconductor materials

Materials	$E_g(0)$ / eV	α (eV/K) ×10^{-4}	β /K
Si	1.1557	7.021	1108
Ge	0.7412	4.561	210
GaAs	1.5216	8.871	572
InP	1.4203	4.906	93

3 Experiment

3.1 Experimental design

Experimental setup is given in Fig.2. For the peak response wavelength of silicon photovoltaic cell is approximate 950 nm, thus a fiber coupled diode laser operating at 940 nm is used. The output power of laser can be adjusted continuously using the current adjusting knob. Collimation lens is used to compress laser divergence. EMP2000 laser power meter with low error is used to measure laser power. A 1 cm × 1 cm single crystal silicon photovoltaic cell is investigated as test unit in the study. In order to control temperature, temperature control card with an accuracy of 0.1 K is utilized. It controls a Peltier heat pump. Under high intensity illumination, a high-efficiency heat changer with water cooling system is also used. The current and voltage signal of photovoltaic cell is measured

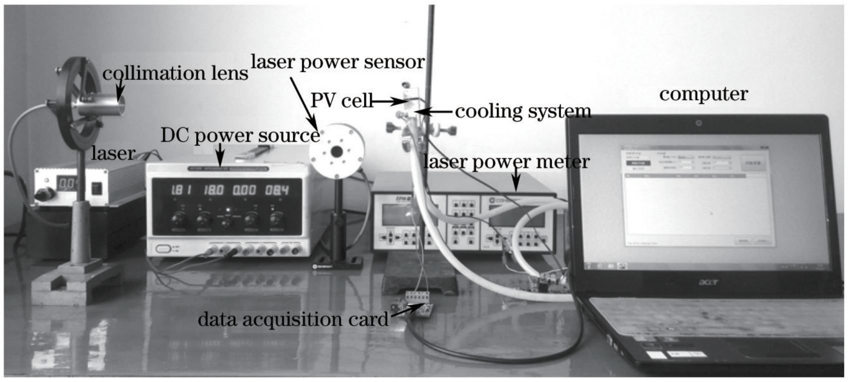

Fig.2 Experimental setup

by data acquisition card connected to a computer.

3.2 Results and analysis

3.2.1 Laser intensity dependence of photovoltaic cell parameters

Figure 3 depicts the variation of short-circuit current of photovoltaic cell with laser intensity P_{in} . Short-circuit current increases linearly with increasing laser intensity in low intensity levels. As laser intensity increases, short-circuit current begins to saturate from a certain laser intensity. As also illustrated in Fig.3, in conditions of different temperatures, laser intensities that short- circuit current begins to saturate from is different. It decreases with increasing temperature. As is pointed out that the saturation can be attributed to the large series resistance[12-13]. Meanwhile, when laser intensity increases, the depletion layer widen and then recombination current increases[14]. Thus, the saturation can be explained in term of high recombination current and large series resistance.

Figure 4 depicts laser intensity dependence of open-circuit voltage at 308 K. It has been observed that open-circuit voltage demonstrates an exponential rise with increasing laser intensity in low intensity levels. The open-circuit voltage begins to decrease from laser intensity of approximate 0.6 W/cm^2. The result has been found to be compatible with the result presented before[10]. It can be explained with the high recombination current under high injection effect condition.

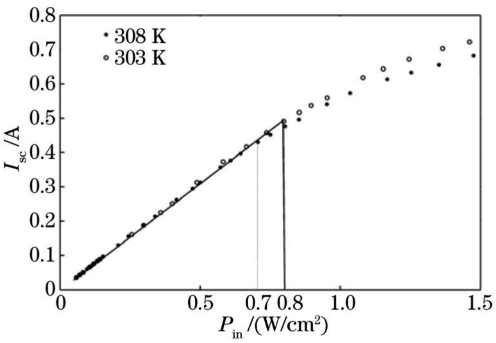

Fig.3 Laser intensity dependence of short-circuit current

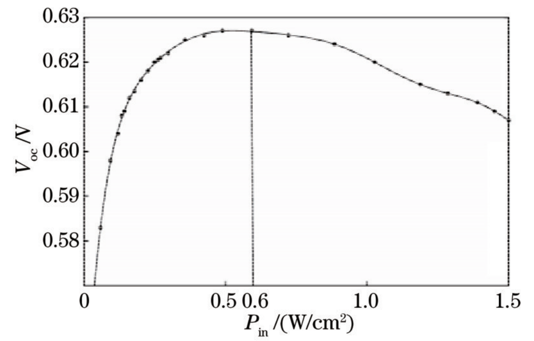

Fig.4 Laser intensity dependence of open-circuit voltage

Laser intensity dependence of efficiency at 293 K is illustrated in Fig.5. Similar trend has also been reported[7,13]. The highest efficiency measured in the experiment is 29.49% at a laser intensity of 0.136 W/cm^2. The decrease in efficiency and such a low laser intensity tolerance can be attributed to high recombination current and power consumption caused by series resistance of photovoltaic cell[13]. In high laser intensity level, efficiency restriction due to high injection effect must be evaluated. Fill factor values are also calculated and a similar trend with efficiency is observed in Fig. 6.

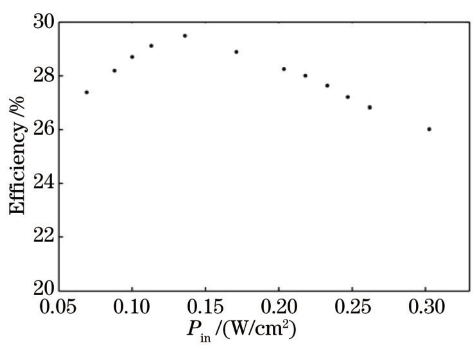

Fig.5 Laser intensity dependence of efficiency

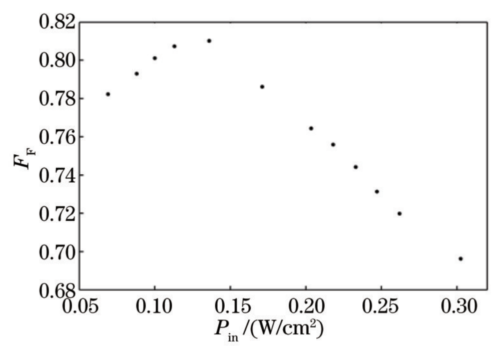

Fig.6 Laser intensity dependence of fill factor

3.2.2 Temperature dependence of photovoltaic cell parameters

Temperature dependence of shot-circuit current for photovoltaic cell is given in Fig.7. In low intensity levels, short circuit current is independent of temperature. A slight increase in short-circuit current of solar cell can be attributed to the decrease in band gap and increasing in absorption coefficient with increasing temperature.

However, for monochromatic light, absorption coefficient is constant despite decrease in bad gap with increasing temperature. Thus, short-circuit current keeps constant. But for high intensity levels, short-circuit current shows a slight decrease with increase in the temperature. Such a behavior is due to high dependence on temperature of recombination current for high intensity levels. The increase in temperature leads to an increase in recombination current and correspondingly a decrease in short-circuit current.

Temperature dependence of open-circuit voltage is illustrated in Fig.8. It shows that open-circuit voltage decreases linearly with increasing temperature. The temperature coefficient of open-circuit voltage is related to laser intensity.

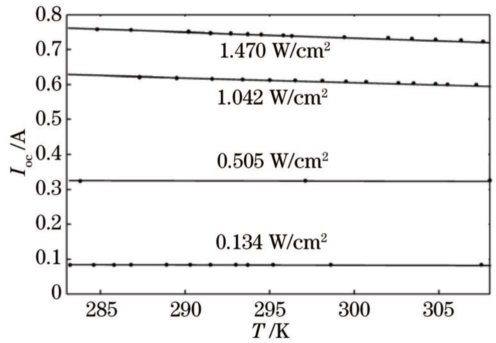

Fig.7 Temperature dependence of shot-circuit current

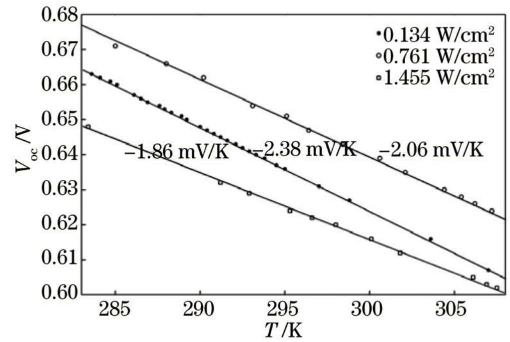

Fig.8 Temperature dependence of open-circuit voltage

Efficiency of photovoltaic cell decreases linearly with increasing laser intensity as shown in Fig.9. Temperature coefficient of efficiency is also affected by laser intensity. It shows that efficiency decreases at lower rate as laser intensity increases. For P_{in} =0.134 W/cm^2, temperature coefficient of efficiency is −0.135%/K whereas it is −0.076%/K for P_{in} = 1.00 W/cm^2. The temperature coefficient of efficiency has a similar tendency with temperature coefficient of open-circuit voltage.

Figure 10 depicts temperature dependence of fill factor of photovoltaic cell. It shows that fill factor decreases with increasing temperature. But, the decreasing rate is different at various laser intensities. The decrease in F_F at low laser intensities levels is mainly affected by decrease in V_{oc} [15] whereas decrease in I_{sc} also contributes to the decrease in F_F at high laser intensities levels.

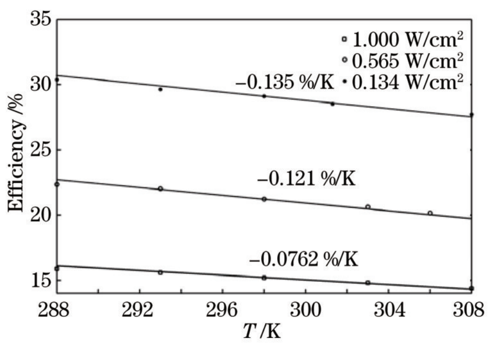

Fig.9 Temperature dependence of efficiency

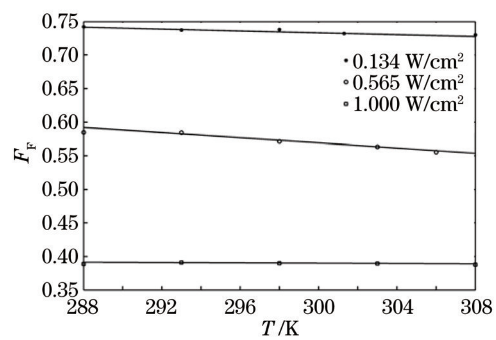

Fig.10 Temperature dependence of fill factor

3.2.3 Series resistance dependence of efficiency

Figure 11 depicts the change in efficiency with series resistance with 1 W/cm^2 laser illumination. It shows that photovoltaic cell efficiency decreases rapidly with increasing series resistance. Thus, a low series resistance is significantly important for high intensity laser illumination.

4 Conclusion

Laser intensity and temperature dependence of parameters of silicon photovoltaic cell are experimentally investigated. A low laser intensity tolerance is found for the tested silicon photovoltaic cell, which can be attributed

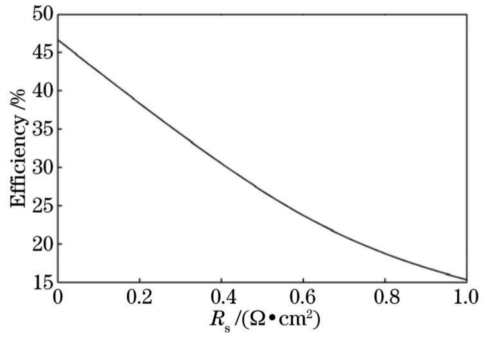

Fig.11 Series resistance dependence of efficiency

to the large series resistance. Both short-circuit current and open-circuit voltage saturate due to high recombination current under high intensity illumination. All four parameters decrease with increasing temperature in high intensity levels. Thus, a high-efficiency cooling method is essential for efficient operation. The study indicates that small series resistance and the reduction of recombination for photovoltaic cell are needed for efficient energy conversion under high intensity laser illumination.

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