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Research paper

Thermal analysis of film photovoltaic cell subjected to dual laser beam irradiation

Yu-Chen Yuan, Chen-Wu Wu*

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

HIGHLIGHTS

- Dual laser beam irradiation was utilized to investigate the PV cell responses.
- Temperature dependency of PV cell output voltage was revealed experimentally.
- Iterative algorithm was set up to compute the laser energy deposition in PV cell.
- The PV cell temperature evolution under laser irradiation was obtained by FEA.
- FEA results agreed well with the experimental results for the test point.

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ABSTRACT

The concept of dual laser beam irradiation was firstly demonstrated on the photovoltaic cell, of which the temperature dependent efficiency was investigated for wireless power transmission. Then, an analytical model was established to calculate the multiple reflection–absorption of any monochromatic light in multilayer structure, and the heat generation in photovoltaic cell was interpreted. Finally, the finite element analysis was used to simulate the temperature pattern of the photovoltaic cell subjected to laser irradiation. The spatial-temporal characteristic of the temperature field was obtained for improving the system in future.

1. Introduction

The wireless power transmission conducted by some high energy beam is viewed as a promising technology serving for many systems, like Unmanned Aerial Vehicle (UAV). Considering the relative small bulk of the equipment and less energy loss in comparison to other concepts [1,2], the laser-based wireless power transmission technology has already attracted the attention of a great many institutions [3–5]. In fact, this technology also sparkle the great ideas of the space solar power station builders [6,7] because they need to find a way to transport the solar energy collected in space to the ground.

The laser-based wireless power transmission equipment mainly consists of two subsystems to convert the electric energy into light energy and then light energy into electric energy. Usually, the electricity-light conversion process is conducted by electro-pumping laser, while the light-electricity conversion is realized by photovoltaic cell (PV cell). The reduction in weight of the power unit has always been aspired for aircraft and space satellite, therefore the III–V family multilayer thin film PV cells are nowadays widely used in these applications. As we know, such thin film PV cells has the advantages of small size, high efficiency and resistance to radiating degradation, deserving to be an ideal choice for practical applications [8,9].

The overall efficiency of the laser-based wireless power transmission system is determined by the two subsystems, of which only the light-electricity conversion efficiency is involved in this article. It is well known that during photoelectric conversion, the high power density of laser beam would result in significant temperature elevation of the PV cell, which would greatly reduce the

* Corresponding author. Institute of Mechanics, Chinese Academy of Sciences, No.15 Beisihuanxi Road, Haidian District, Beijing 100190, China. Tel.: +86 10 82544271.
E-mail addresses: chenwuwu@imech.ac.cn, wuchenwu@gmail.com (C.-W. Wu).

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efficiency of the cell. The main reason is that the temperature elevation would reduce greatly the open-circuit voltage of the cell [10,11] and its fill factor [12,13]. In addition, temperature elevation would develop thermal stress in PV cells due to the mismatch in thermal expansion of the materials. The thermal stress would also influence the cell efficiency, as well as cause physical damage in cell and even lead to permanent failure of the cell [14–16]. Therefore, it is very important to comprehend the temperature characteristics of the cell under laser irradiation in order to improve the overall performance of laser-based wireless power transmission system. Moreover, the commonly used multi-junction PV cells always have multiple absorption peaks for the incident laser beams of different wavelengths. Therefore, it is promising to use multiple laser beams to increase the efficiency of the laser-based wireless power transmission system. A typical experiment was developed to investigate the outcome of PV cell subjected to dual laser beams of wavelengths around its absorption peaks [17]. It was revealed preliminarily that the second laser beam did increase the outcome voltage of the PV cell and an obvious inflection point had been observed in the voltage curve, which is believed to be largely dependent on the thermal effect.

This article firstly demonstrates the utilization of dual laser beams of different wavelength, around the double absorption peaks of the thin film PV cell in the light-electricity conversion experiment. Then, the model of multiple reflection–absorption of any monochromatic light in multilayer structure has been established, and the analytic solution of laser energy absorption of each layer in the thin film PV cell has been obtained. Finally, the heat generation in the PV cell during energy conversion is described and the finite element method has been used to simulate the temperature pattern of the PV cell under laser irradiation. The spatial-temporal characteristics of the temperature field are obtained, which is of importance for improving the wireless power transmission system in future.

2. Experimental description and results

In the experiment, GaInP/GaAs/Ge three-junction thin film PV cell has been used, of which the absorption peak of GaInP junction and Ge junction appears for the incident light of wavelength about 500 nm and 1000 nm, respectively. Correspondingly, the two laser beams of wavelengths 532 nm and 1064 nm are utilized, in which the maximum output power is about 30 mW for the shorter wavelength laser and about 25 W for the longer wavelength laser. Therefore, the higher power laser could be in particular exploited to make a quick temperature ascending circumstance for the thermal effect study. The sketch of the PV cell structure is shown in Fig. 1. Moreover, the PV cell of overall dimensions 11 mm × 11 mm × 170.184 μm is adhered by a 5 μm adhesive layer to the aluminum plate of dimensions 50 mm × 35 mm × 1.75 mm.

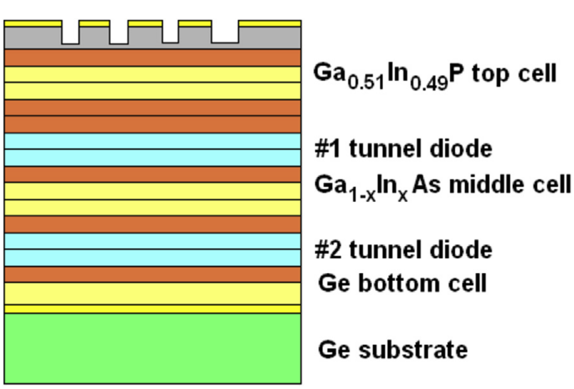

Fig. 1. GaInP/GaAs/Ge photovoltaic cell structure.

In structure, the main body of the cell includes the GaInP junction, GaInAs junction, Ge junction and Ge substrate layer. The layer thicknesses of the PV cell are listed in Table 1.

The two laser beams were regulated to irradiate the cell surface almost vertically and fall upon nearly the same spot as shown in Fig. 2, in which the angle between the two beams has been exaggerated for illustration. During test, both the surface temperature at the point 3 mm away from the center of laser beam covered region and output voltage of the PV cell were continually monitored and recorded. At the beginning of the experiment, the cell was subjected to irradiation by the 532 nm laser of maximum power 30 mW. When the output voltage was stable, the 1064 nm laser of maximum power 25 W was also started to irradiate the cell. After temperature and output voltage have reached some steady values, turn off the 1064 nm laser and keep on recording the temperature and output voltage till the cell was cooled down naturally. Fig. 3 shows the typical experiment results of voltage output and temperature, respectively. To be noted that the test data are cut at the instant shortly before the action of the large power laser to avoid too much redundancy.

As shown in Fig. 3, the initial voltage (about 1.6 V) was generated by the irradiation of 532 nm laser. After starting the 1064 nm laser, a temporary increasing appeared in the voltage curve, which means the dual-wavelength laser irradiation could actually improve the total voltage. While the cell voltage decreases sharply with the rapid rising of its temperature after starting the 1064 nm laser. The cell voltage drops down to zero when the test point temperature reaches about 387 K. It is indicated that such temperature elevation of the cell would inhibit its photoelectric conversion. Later on, the cell experienced a natural cooling procedure and the voltage finally recovered to the initial level after removing the long-wavelength laser. It shows that the decline of the output voltage could be eliminated by decreasing the temperature if the deposited laser energy does not reach the damage threshold of the cell. However, permanent damage would arise if the temperature exceeds critical magnitude [16,17] and the PV cell would fail permanently. Therefore, we need to predict accurately the temperature pattern of the cell under laser irradiation. Moreover, one can see that the test point temperature is almost stable before the action of higher power laser, which means that the heat generation would be accurately predicted theoretically without considering the influence of the lower power laser.

Table 1
Layer thicknesses of the PV cell.

Junction layer	Sub-layer	Thickness
GaInP, 1.6 μm	AlInP	0.04 μm
	n-GaInP	0.5 μm
	p-GaIn	1 μm
	p + -GaInP	0.03 μm
	p + -AlGaInP	0.03 μm
GaInAs, 7.584 μm	p++-AlGaAs	0.006 μm
	n++-GaInAs	0.006 μm
	tunneling junction	0.012 μm
	n + -AlGaInP/AlInAs	0.03 μm
	n-GaInAs	0.5 μm
	p-GaInAs	7 μm
	p + -GaInAs	0.03 μm
Ge, 21.024 μm	p++-AlGaAs	0.006 μm
	n++-GaInAs	0.006 μm
	tunneling junction	0.012 μm
	n-Ge	2 μm
	p-Ge	19 μm
Ge substrate, 140 μm		140 μm

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