Influence of thermal effect on multi-junction GaInP/GaAs/Ge concentrating photovoltaic system

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The influence of thermal effect on the energy conversion efficiency of concentrating photovoltaic system for multi-junction GaInP/GaAs/Ge thin-film solar cell is analyzed experimentally. With the increment of operation temperature, the maximal energy conversion efficiency and optimal loaded resistor will be changed. Under the condition of operation temperature lower than 90 °C, this influence of thermal effect is very small. However, when the operation temperature exceeds 90 °C, the maximal conversion efficiency of the cells will decrease sharply, and contrarily the corresponding optimal loaded resistor will increase quickly. Then the system performance will degenerate badly and a thermal management will be necessary.

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With the rapid development of world economy, more and more attention has been paid to the problems of energy. Nowadays, the fossil energies, such as petroleum, coal, and gas, are reducing sharply and it is estimated that their reserves only can maintain about decades for human requirements. For example, based on the statistic and measurement of authoritative organization, petroleum remains about 1000 billion barrels and can be used for 40 years, gas is about 180000 billion cubic meters for 60 years, and coal is 900 billion tons for 300 years in the earth[1]. It will be a very pressing problem for searching new alternative energy. Solar energy[2−4], as a clean and inexhaustible energy in supply and use, has been regarded as one of the ideal choices for future energy requirement. Currently, although the usages of solar energy include all kinds of means, the photovoltaic technology is the most attractive and rapidly developing industry in recent years.

So far, the development of photovoltaic technology has experienced the conventional monocrystalline silicon solar cell and the thin-film solar cell based on semiconductor technology[5−7]. Compared with the monocrystalline silicon solar cell, the thin-film solar cell possesses higher conversion efficiency, smaller volume, lower contamination, and larger profit. However, a limiting factor is that the materials needed for thin-film cells, such as III-V multi-junction GaInP/GaAs/Ge solar cell[8,9], are very expensive, thus usually their installed area is very small for each unit (less than 100 mm^2). In order to satisfy this small size, some optical assistant systems such as mirrors, lenses, and prisms are necessary, which can concentrate sunlight on the cell by a thousand times. This concentration photovoltaic (CPV) technology can reduce the quantity of expensive semiconductor material and use relatively inexpensive optics, and increase the power density of solar radiation and improve the energy conversion efficiency. Many experiments and researches have proved that the efficiency of CPV technology may exceed 40%, double of that of conventional monocrystalline silicon solar cells. However, the problem brought from this CPV technology is thermal management[10−12]. High operation temperature will quickly reduce the conversion efficiency of solar cell and shorten its life-span. In this letter, the influence of thermal effect on the conversion efficiency of CPV system for multi-junction GaInP/GaAs/Ge solar cell is analyzed in detail. With the increment of operation temperature, the maximal conversion efficiency of the system shows a slow change firstly; however, when the operation temperature exceeds 90 °C, the conversion efficiency will reduce sharply. Then the system performance will degenerate badly and a thermal management becomes necessary. On the contrary, the corresponding loaded resistor to obtain the maximum energy conversion efficiency will add quickly in our experimental system.

The typical photovoltaic systems are flat-plate photovoltaic panels which are fixed on roof-tops. These photovoltaic systems are costly, covered with solar cells. They rely upon the direct illumination of sunlight on the entire surface of the photovoltaic panels[5]. Unlike these typical photovoltaic systems, the CPV technology uses a concentrator that is located between the sun and the solar cells to concentrate and magnify sunlight onto the solar cells. They can achieve sizes 250–500 times smaller than the typical "one-sun" photovoltaic solar panels. This CPV technology effectively replaces the expensive semiconductor solar materials with some inexpensive plastic lenses, such as Fresnel lens. Figure 1 shows the principle of a CPV system consisting of three main parts: concentrator, solar cell, and heat sink. Under the concentrating condition of sun light, the conversion efficiency of the cells will increase with the increase of radiation power density per unit area on the cell, then the corresponding conversion efficiency of solar cell is[13,14]

$$\eta_{\mathrm{c}}=\frac{V_{\mathrm{c}}I_{\mathrm{c}}F}{xP_{\mathrm{in}}}\approx\frac{mkTI_{\mathrm{s}}}{eP_{\mathrm{in}}}\left(1-\frac{mkT}{eV_0}\right)\left[\ln\left(\frac{I_{\mathrm{s}}}{I_0}\right)+\ln x\right]\Bigg|_{R\to 0}, \quad (1)$$

where V_{c} is the output voltage, I_{c} is the output current, V_0 is the open-circuit voltage, I_{s} and I_0 are short-circuit current and dark current, $1< m <2$ is an ideal factor which is associated with the photo-generation carriers, e is the electron charge, T is the temperature, k is the Boltzmann constant, x is the concentrating ratio of solar cell, P_{in} is the incident power of sun light, F and R are

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the filling factor and the loaded resistor, respectively. When the loaded resistor is very small, it is found that the conversion efficiency of solar cell will have a logarithmic relation with the increment of concentrating ratio. In the following contents, we will research the influence of thermal effect on the performance of this CPV system by analyzing the maximal conversion efficiency and the optimal loaded resistor. Figure 2 shows an experimental scheme. The used solar cell was a triple-junction GaInP/GaAs/Ge thin-film solar cell[10] and its effective area was about 25 mm^2. This cell was stuck on a heat sink by the thermal conductive adhesive and they were fixed on a temperature control device together. This temperature control device may adjust the temperature of solar cell flexibly and accurately to simulate the temperature variation due to the radiation of sun light. Two electrodes of cells were connected by a variable resistor (26–1000 Ω tunable) and a current meter to form a close loop. The voltage of variable resistor was monitored by a voltage meter. In order to measure the thermal characteristic of solar cell under a long-time stable condition and simplify the corresponding sun-tracker, a 100-W white-light lamp was used to simulate the sun although its intensity was weaker than the sun radiation. The light from the lamp was firstly collimated by a lens and then focused on the surface of cell by a Fresnel lens. The diameters of two lenses were 10 cm.

Adjusting the cell temperature to 30 °C by the temperature control device and changing the loaded value of variable resistor, the corresponding changes of current and voltage in the loop were recorded, as shown in Fig. 3(a). With the increment of loaded resistor, the current in the loop kept invariable firstly for about 26 mA. However, the voltage of loaded resistor increased quickly from 0.7 to 2.5 V (the minimal value of variable resistor was 26 Ω) and then the conversion efficiency also increased correspondingly. When the loaded resistor was adjusted to about 97 Ω, the increment of the voltage would be very slow and contrarily the current began to reduce quickly. Then the conversion efficiency would also reduce. Figure 3(b) shows the variation of the conversion efficiency versus the loaded resistor. The maximal conversion efficiency was about 31.3% in the tested system without considering the energy loss of the optical system when the loaded resistor was adjusted to 97 Ω. This resistor was also called the optimal loaded resistor. Reducing the temperature of cells continuously from 30 to 0 °C by the temperature control device, it was found that the parameters of the tested system, including the voltage, current, maximum conversion efficiency, and optimal loaded resistor, had a very small change. Therefore, under the condition of low temperature, the influence of thermal effect on the performance of this triple-junction GaInP/GaAs/Ge thin-film solar cell will be very small. This case may be corresponding to the low-temperature CPV system.

In order to research the influence of thermal effect on the performance of multi-junction solar cell quantitatively for a high-temperature CPV system, the cells were heated by adjusting the temperature control device to different temperatures. The corresponding changes of voltage, current, and conversion efficiency versus the loaded resistor are shown in Fig. 4 for 50, 70, 90, and 110 °C, respectively. Figure 5 shows the statistical results of the maximal conversion efficiency and the optimal loaded resistor versus temperature. With the increment of operation temperature, both the maximum conversion efficiency and the optimal loaded resistor reduce slowly. At the same time, the stable current value in the initial moment for low temperature would disappear gradually.

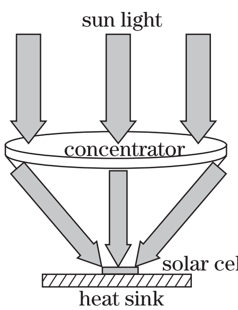

Fig. 1. Principle of concentrating photovoltaic system.

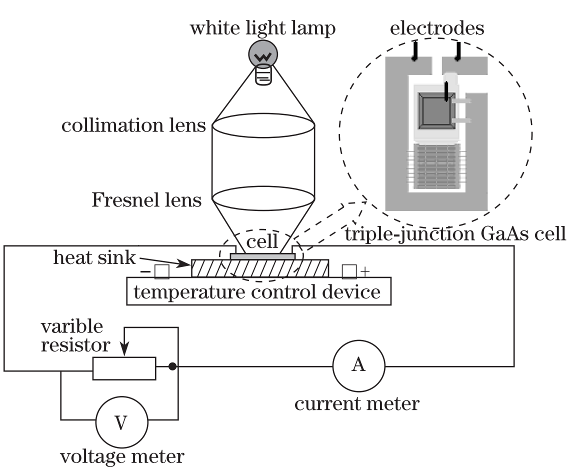

Fig. 2. Schematic diagram of experimental setup.

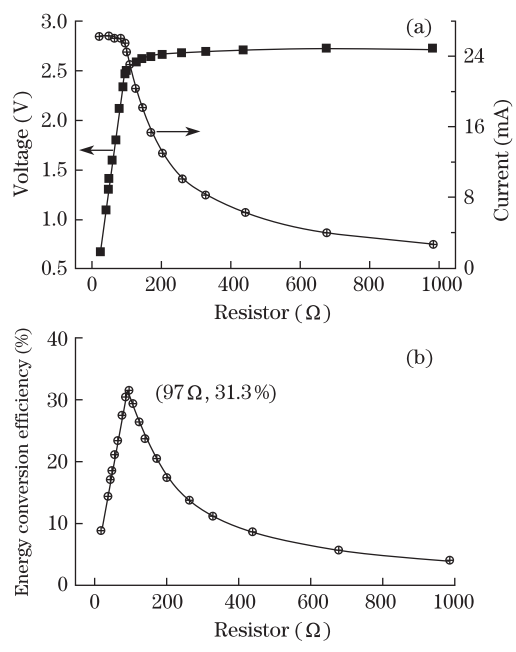

Fig. 3. (a) Voltage and current versus the loaded resistor at 30 °C; (b) conversion efficiency in the loop versus the loaded resistor.

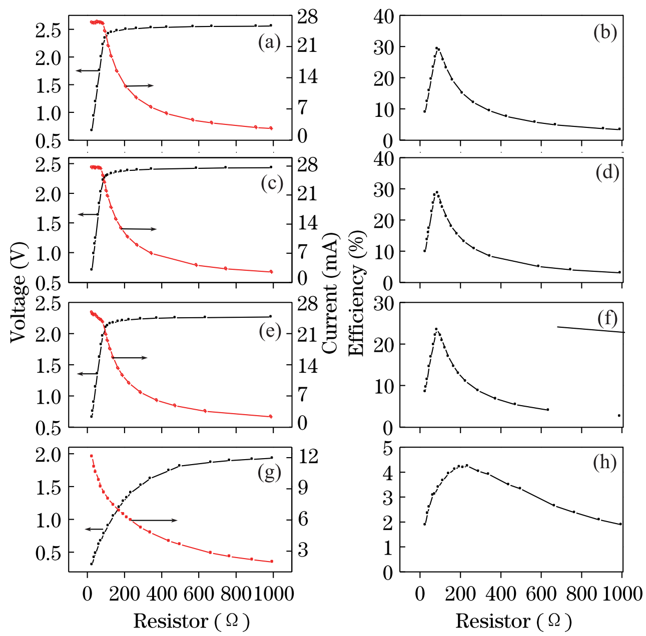

Fig. 4. Voltage, current, and conversion efficiency versus the loaded resistor. (a), (b) 50 °C; (c), (d) 70 °C; (e), (f) 90 °C; (g), (h) 110 °C.

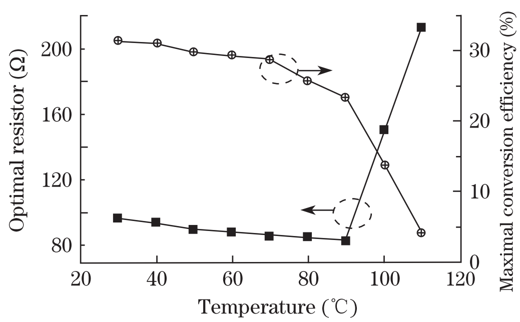

Fig. 5. Statistical results of maximal conversion efficiency and optimal loaded resistor versus temperature.

When the operation temperature is about 90 °C, their values are 23% and 83 Ω, respectively. Compared with the case of 30 °C, this result is not very serious. Heating the cells continuously, the maximum conversion efficiency in the tested system would reduce sharply and contrarily, the optimal loaded resistor would increase quickly. When the operation temperature achieves about 110 °C, the maximum conversion efficiency is only 4.15% and this value is only 13.3% of that at 30 °C. The corresponding optimal loaded resistor is 213 Ω. The reason is that each light source has the corresponding emission spectra and the response range of solar cells covers only a small wave-band. The bandgap of semiconductor materials would be reduced with the increment of operation temperature, and the corresponding response wave-band of cells would shift to long-wavelength direction. This is the main factor that causes the pronounced decrease of cell efficiency for high operation temperature (i.e., negative temperature coefficient[11,12]). This process will deteriorate further for higher operation temperature. Therefore, a high operation temperature has a very serious influence on the performance of multi-junction solar cell and a cooling device will be very necessary. This case is similar to the high-temperature CPV system in practical application. Moreover, the loaded resistor in the loop has also a large effect on the conversion efficiency for the same condition (e.g., temperature) and an optimal value would also exist.

In conclusion, the influence of thermal effect on the CPV system for triple-junction GaInP/GaAs/Ge solar cell is investigated experimentally. With the increase of temperature, the maximal energy conversion efficiency of solar cell has a slight change firstly. However, when the cell operation temperature exceeds 90 °C, this efficiency would decline sharply. Then the performance of system would degenerate quickly and a thermal management would be necessary. Moreover, the optimal loaded resistor for obtaining the maximum conversion efficiency would also increase quickly for the loop in the tested system.

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