Thermal analysis and test for single concentrator solar cells

Cui Min(崔敏)[1,†], Chen Nuofu(陈诺夫)[1,2], Yang Xiaoli(杨晓丽)[1], Wang Yu(汪宇)[1], Bai Yiming(白一鸣)[1], and Zhang Xingwang(张兴旺)[1]

(1 Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China)

(2 National Laboratory of Microgravity, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China)

Abstract: A thermal model for concentrator solar cells based on energy conservation principles was designed. Under 400X concentration with no cooling aid, the cell temperature would get up to about 1200 °C. Metal plates were used as heat sinks for cooling the system, which remarkably reduce the cell temperature. For a fixed concentration ratio, the cell temperature reduced as the heat sink area increased. In order to keep the cell at a constant temperature, the heat sink area needs to increase linearly as a function of the concentration ratio. GaInP/GaAs/Ge triple-junction solar cells were fabricated to verify the model. A cell temperature of 37 °C was measured when using a heat sink at 400X concentration.

Key words: heat sink; cooling; concentrator solar cells; thermal dissipation
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1. Introduction

Tandem solar cells using a concentrator–a field known as concentrator photovoltaics (PV)–provide the possibility to realize a very efficient PV system at low cost. In such systems, the cost of the generated electricity can be significantly reduced by replacing expensive PV cell area with less expensive optical material. In addition, a significant improvement of the PV performance is also expected at a suitable concentration, as was recently demonstrated by King *et al.*[1], who reported a never before achieved conversion efficiency of 40%. However, the use of a high concentration inevitably gives rise to a considerable increase of the cell temperature during operation due to the finite conversion efficiency. The generated Joule heat may lead to a potential degradation of the PV performance[2,3]. Therefore, the system needs to be cooled during operation.

Passive and active cooling are the two possible methods for removing heat from high-illumination photovoltaic cells. In passive cooling[2,4,5], the surrounding air circulates over a heat sink mounted on the cell. Active cooling[4,6,7] usually involves circulating cooling water through a thermally conductive tube upon which the cells are mounted[8]. Typically, single cells only needs passive cooling even for very high solar concentrations[9] because of their small size. Passive cooling also has the advantage of cost efficiency[10]. However, there are only a few reports on the thermal analysis of single concentrator solar cells. In this work, a thermal model for concentrator solar cells based on energy conservation principles is proposed. The temperature dependence of the cell on the area of the heat sink for different concentration ratios is studied. These results are important with regard to the design of the passive cooling of the solar cell system. The results of outdoor experiments, carried out to verify the model, are presented.

2. Thermal model

In concentrator solar cells, the sunlight is concentrated by mirrors or lenses, as shown in Fig. 1 for the example of a lens. In Fig. 1, the lens concentrates the sunlight onto the cell to increase the light density at the cell surface. The cell reaches its steady-state temperature when the luminous power absorbed is equivalent to the sum of the electric power delivered to the load plus the power dissipated in the form of heat. Heat dissipation takes place by radiation and convection. When thermal equilibrium is reached, the conservation equation for concentrator solar cells is as follows:

$$\tau\alpha A_0 C q_0 - \eta\tau\alpha A_0 C q_0 - A_r \varepsilon\sigma(T^4 - T_0^4) - A_c h(T - T_0) = 0, \quad (1)$$

where the first term denotes the luminous power absorbed by the cell with the lens transmissivity τ, the cell surface absorptivity α, the cell area A_0, the lens' geometric concentration ratio C and the energy density q_0. The second term in the equation is the electric power delivered to the external

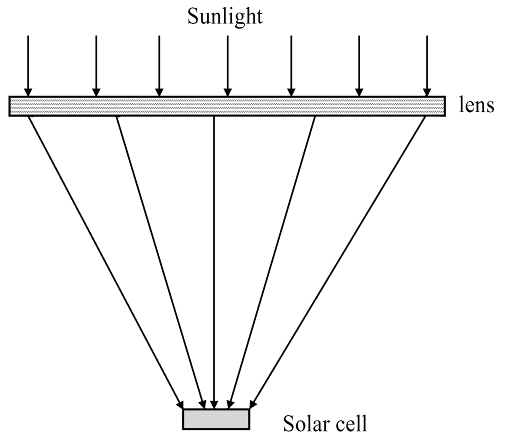

Fig. 1. Solar cell under concentration.

† Corresponding author. Email: mcui@semi.ac.cn
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Table 1. Some parameters used in the model.

Parameter	Description	Value
τ	Transmissivity of the optical collector	0.8
α	Surface absorptivity of the cell	0.85
A_c	Area of the cell	3×3 mm^2
q_0	Energy density	AM1.5
σ	Stephan-Boltzmann constant	5.67×10^{-8} W/(m^{2}K^4)
T_0	Ambient temperature	300 K
h	Convective transfer coefficient	5 W/(m^{2}K)[11]

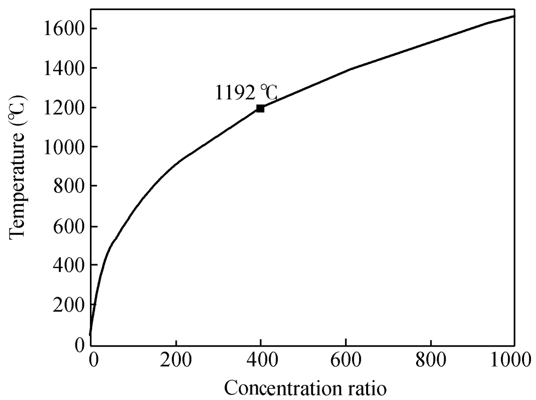

Fig. 2. Cell temperature under concentrated illumination with no cooling aid according to our model.

load with the conversion efficiency η. The third term represents the power dissipated through radiation with the surface area A_r, the surface emissivity ε, the Stephan-Boltzmann constant σ, the surface temperature T and the ambient temperature T_0. The last term characterizes the power dissipated through convection, which depends on the surface area A_c and the convective transfer coefficient h. Table 1 shows the values of some parameters in the model.

The conversion efficiency of photovoltaic solar cells decreases as the temperature increases. It was reported that the efficiency decreases from 18.4% to 4.4% as the temperature increases from 300 to 500 K[3]. Most models assume that there is a linear decrease in efficiency with temperature[10–12]. In our model, the linear decrease in efficiency with temperature was assumed to be given by

$$\eta = a(1 - bT), \tag{2}$$

where a and b are linear parameters (with $a = 0.425$ and $b = 0.00176$)[3].

When there is no cooling aid for the concentrator system (as shown in Fig. 1), the heat dissipates only through radiation and convection from the cell surface. Figure 2 shows the cell temperature according to Eqs. (1) and (2) under concentrated illumination for the case that both sides of the cell contribute to the heat dissipation. The cell temperature increases remarkably with an increase in the concentration ratio. When the concentration ratio is 400, the temperature of the cell is as high as 1200 °C. Such a high temperature is fatal for any solar

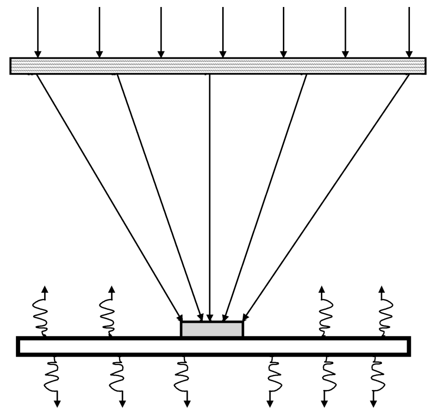

Fig. 3. Schematic diagram of the concentrator solar cell system with a heat sink.

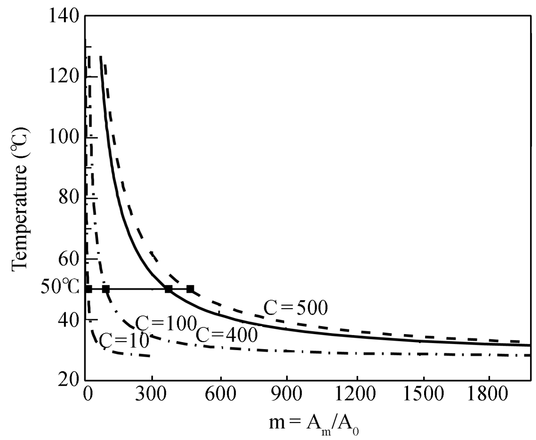

Fig. 4. Dependence of the cell temperature on the ratio of the heat sink surface area to the cell surface area.

cells. Therefore, a means for passive cooling was studied in this work.

As shown in Fig. 3, a metal plate was used to dissipate heat from the concentrator solar cell. The cell and the heat sink are connected with a thin thermally-conductive adhesive. To calculate the cell temperature in case a heat sink is used, some assumptions were made:

(1) The heat transfer of the side faces of the heat sink is ignored.

(2) The conversion efficiency of the cell is a constant of 30%.

(3) The surface of the metal plates is coated with black paint ($\varepsilon = 0.9$).

(4) The temperature of the cell is approximately equal to the average temperature of the heat sink[13].

As shown in Fig. 3, the heat will dissipate by radiation and convection from the surface of the heat sink. We define m as the ratio of the heat sink surface area to the cell surface area given by

$$m = \frac{A_m}{A_0}. \tag{3}$$

Figure 4 shows the dependence of the cell temperature on m for different concentration ratios. As shown in Fig. 4, with an increase of the heat sink area, the temperature of the cell decreases at the beginning and later changes gradually. Keeping

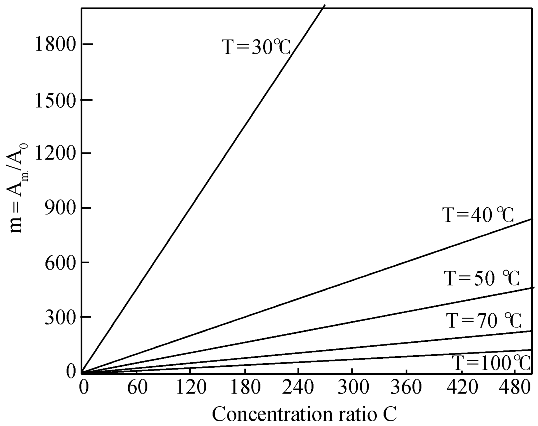

Fig. 5. Linear relation of the heat sink area to the concentration ratio.

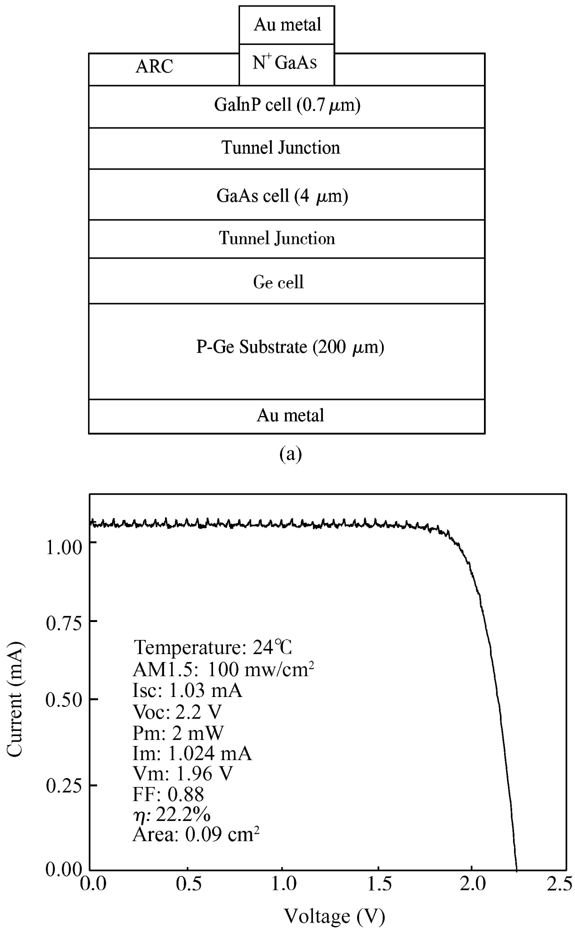

Fig. 6. (a) Schematic structure and (b) performance of the GaInP/GaAs/Ge triple junction cell.

the cell temperature at 50 °C and changing the concentration ratio from 10 to 500, m would increase from 14 to 479.

The relation between m and the concentration ratio is shown in Fig. 5 for the case of a fixed cell temperature. According to our model, the heat sink area would increase linearly with the concentration ratio in order to keep the cell temperature at a certain value. We can also see that the slope of the lines is steeper at lower temperatures. That is to say, if we increase the concentration ratio and at the same time try to keep the temperature low to get a higher conversion efficiency of the solar cells, we need a heat sink with a larger area.

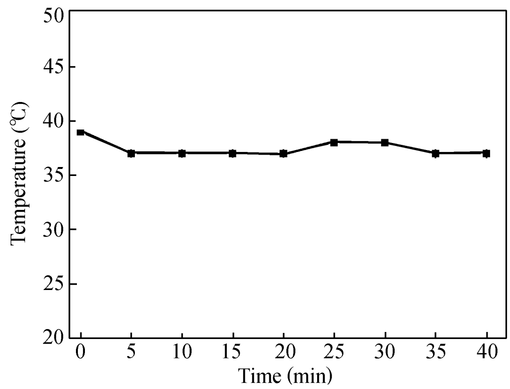

Fig. 7. Temperature variation over time for the cells.

3. Experiment

The GaInP/GaAs/Ge triple-junction solar cells (3 × 3 mm^2) used for this study were grown on a p-type Ge substrate using metal organic chemical vapor deposition (MOCVD). Figure 6 shows the schematic illustration and the performance of the GaInP/GaAs/Ge triple-junction cell.

The temperatures of the cells using 400X concentration and a heat sink were tested outdoors. The area of the heat sink was 700 times larger than the solar cell area. The heat sink was made of aluminum with black coating. The temperatures of the upper surface of the solar cells were measured using a Pt100 sheet temperature sensor having an accuracy of 1 K. Figure 7 shows the measured temperature of the solar cell as a function of time. The temperature of the cell was about 37 °C. According to the simulated results in Fig. 4, the temperature of the cell having an area ratio of 700 and using a 400X concentration is about 40 °C. The model is thus able to predict the temperature for this setup.

4. Conclusion

A thermal model for concentrator solar cells based on energy conservation principles is proposed. Based on the model, the cell temperature will reach about 1200 °C when a 400X concentration factor and no cooling aid are used. When heat sinks are used in the system, the cell temperature can be significantly reduced. The results show that for a certain concentration ratio the cell temperature reduces when using a larger heat sink. For a certain fixed cell temperature, the heat sink area depends linearly on the concentration ratio. In order to verify the model for one concentration and one heat sink size, outdoor temperature testing of a GaInP/GaAs/Ge triple-junction solar cell using a 400X concentration was carried out. The measured temperature is well predicted by our model.

The results of this work are significant for the design of passive cooling elements in the field of single concentrator solar cells.

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