Characteristics of GaAs Concentrator Cells for High-intensity Laser

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Abstract: - High efficiency GaAs concentrator cells are useful for numerous applications requiring isolated power and voltage, or transmission of power without electromagnetic interference. This paper concerns the characteristics of GaAs concentrator cells illuminated by high-intensity laser beams. The objectives of this study are to identify and understand the mechanisms which limit the performance of GaAs concentrator cells for high-intensity laser. A modeling process is proposed to configure a computer simulation model based on the fundamental characteristics of photovoltaic (PV) cells, which is able to demonstrate the GaAs concentrator cell's output features under the effects of series resistance and temperature. Both factors inevitably degrade the conversion efficiency of GaAs cells. The results indicate that the laser light intensity gets higher, the series resistance becomes smaller, while the effect of series resistance for the conversion efficiency becomes serious. In addition, the conversion efficiency also decreases as the temperature increases due to the temperature dependency of the open circuit voltage. For GaAs concentrator cells, there is a very good linearity between the open circuit voltage and the temperature, and at the same time, the conversion efficiency change rate is roughly proportional to the open circuit voltage change rate.

Key-Words: - GaAs concentrator cells, High-intensity laser, Series resistance, Temperature dependency.

1 Introduction

Optical power transmission is a useful technology which has penetrated fields of research such as transmission of energy by optical fibers and through space [1]. There are many important applications such as electric power, remote sensing and aerospace, in which PV cells based on semiconductor heterostructures previously developed for conversion of concentrated sunlight are illuminated by monochromatic laser light due to their capacity to efficiently convert high power laser emission into electricity [2]. PV cells transform optical power into electrical power, which is inherently immune to EMI, RF, lightning effects, and high voltage [3]. Thus, this technology is also readily available for safe and arm applications since it is immune to magnetic fields, electrical noise and conduction of unexpected electrical currents. Another significant advantage is that the output voltage of PV cells is determined by their materials, and it is almost constant even if the optical input power varies a little. The voltage fluctuation of optical powering is much less than that of electrical powering [4].

In order to obtain higher electrical power, PV cells especially designed for working under very high intensity monochromatic light sources are necessary. III-V direct bandgap semiconductors are specifically tailored for the development of very efficient PV cells designed for high intensity monochromatic conversion. This is because of the high performance of their optoelectronic characteristics and their stability over a wide temperature range. Out of all of the III-V materials, the theory and technology transference from GaAs concentrator solar cells could make the work of monochromatic converters at high power density feasible [5], so nowadays it is the principal material used to develop optical power transmission systems. Walker have obtained a 45% conversion efficiency with a laser power density of 2.45 W/cm^2 [6], Olsen have obtained a 52.1% efficiency with a laser power density of 100 mW/cm^2 [7], and some other authors used monolithic series-connected GaAs concentrator cells with large output voltages.

The purpose of our work is to develop high current density laser power converters intended for operation in GaAs concentrator cells. Therefore, this article concerns the characteristics of GaAs concentrator cells for high-intensity laser beams. A detailed discussion about the limiting efficiencies of GaAs cells under high-intensity laser illumination is presented with a calculation method based on the fundamental characteristics of a PV cell.

2 Mathematical Model

The traditional models of PV cells represented by a current source in parallel with one or two diodes are shown in Fig.1. The single-diode model shown in Fig.1 (a) includes four components: photo current source, diode parallel to the source, series resistor R_s and shunt resistor R_{sh}. In double-diode model shown in Fig.1 (b), an extra diode is added for better curve fitting [8]. In most cases, due to the exponential equation of a p-n diode junction, it is difficult to determine these five parameters in single-diode model or six parameters in double-diode model mathematically. Since the shunt resistance R_{sh} is large, so it usually can be neglected [9]. The single-diode model and double-diode model can, thus, be simplified into Fig.1 (c), an equivalent-circuit model of this study.

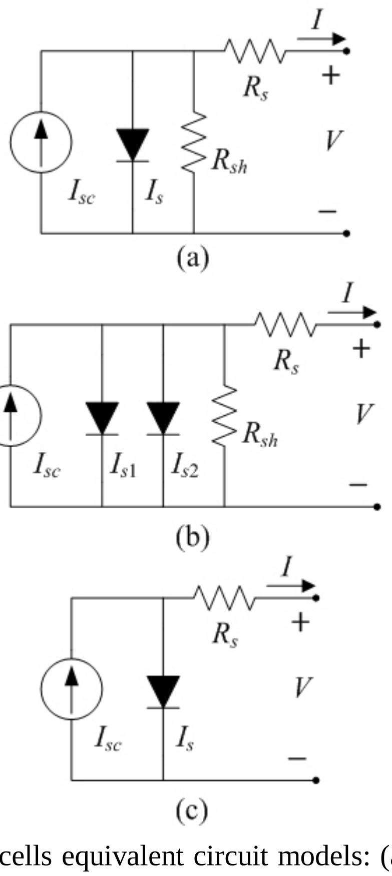

Fig.1 PV cells equivalent circuit models: (a) single-diode model, (b) two-diode model, (c) simplified equivalent model

The most efficient conversion efficiency can be obtained by illuminating PV cells by a laser light with the cutoff wavelength [10]. The cutoff wavelength is determined by the energy gap of the PV cell material:

$$\lambda_c = hc/qE_g \tag{1}$$

where h is the Planck constant, c is the velocity of light in vacuum, q is the electronic charge, and E_g is the bandgap energy in electron volts.

The GaAs concentrator cells exhibit a long wavelength excitation threshold about 900 nm, rise to peak conversion efficiency at the wavelength of 870 nm, and drop to half peak conversion efficiency at the wavelength of 300 nm.

At a certain optical power P_{in} with the wavelength λ, the short circuit current I_{sc} for an ideal PV cell is given by:

$$I_{sc} = \frac{q\lambda}{hc} P_{\text{in}} Q_{ext}(\lambda) \tag{2}$$

where $Q_{ext}(\lambda)$ is the external quantum efficiency (QE), which can be improved by the suppression of recombination.

The spread in values of the open circuit voltage V_{oc} for PV cells is mainly attributed to variations in temperature. To consider the temperature variation of V_{oc} in greater detail [11], we use the relation:

$$\frac{dV_{oc}}{dT} = \frac{V_{oc} - E_g(T)}{T} - \frac{3k}{q} - \frac{\alpha T(T+2\beta)}{(T+\beta)^2} + \frac{kT}{qI_{sc}}\frac{dI_{sc}}{dT} \tag{3}$$

where $E_g(T)$ is the bandgap at temperature T, k is the Boltzmann constant, α and β are constant.

The temperature dependency of $E_g(T)$ is represented as:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{(T+\beta)} \tag{4}$$

According to the simplified equivalent circuit model of PV cells, the illuminated current I and voltage V are represented as:

$$I = I_{sc} - I_s\left(\exp\left(\frac{V+IR_s}{V_t}\right) - 1\right) \tag{5}$$

where $V_t = nkT/q$, on the assumption that T = 300K and n = 1, $V_t \approx$ 25mV, I_s, R_s and n are the saturation current, series resistance, and ideality factor, respectively.

In respect that $\exp\left((V+IR_s)/V_t\right) \gg 1$, the illuminated current I and voltage V can be represented as:

$$I = I_{sc} - I_s \exp\left(\frac{V+IR_s}{V_t}\right) \tag{6}$$

At the open circuit state, the saturation current I_s is obtained as:

$$I_s = I_{sc} \exp\left(-\frac{V_{oc}}{V_t}\right) \tag{7}$$

The output electrical power P_{out} of PV cells is given by $P = IV$. In principle, the current I_m and the voltage V_m at the maximum output power can be obtained from the condition of dP/dV = 0, but the educed expressions are great complexity. According to M. A. Green [12], one empirical expression can be used to represent this relation:

$$FF_c = \frac{I_m V_m}{I_{sc} V_{oc}} = \frac{P_m}{I_{sc} V_{oc}} = FF_0\left(1 - r_s\right) \quad (8)$$

where $FF_0 = \frac{v_{oc} - \ln\left(v_{oc} + 0.72\right)}{\left(v_{oc} + 1\right)}$, $v_{oc} = \frac{V_{oc}}{V_t}$, $r_s = \frac{R_s I_{sc}}{V_{oc}}$.

Using equation (8), the series resistance is given by:

$$R_s = \left(1 - \frac{FF}{FF_0}\right)\frac{V_{oc}}{I_{sc}} \quad (9)$$

According to G. Araujo [12], the current I_m and the voltage V_m at the maximum output power can be represented as:

$$\frac{V_m}{V_{oc}} = 1 - \frac{b}{v_{oc}}\ln a - r_s\left(1 - a^{-b}\right) \quad (10)$$

$$\frac{I_m}{I_{sc}} = 1 - a^{-b} \quad (11)$$

where $a = v_{oc} + 1 - 2v_{oc} r_s$, $b = a/(1+a)$.

All expressions mentioned above would be effectual, on condition that $v_{oc} > 15$ and $r_s < 0.4$. In general, the precision is higher than 1% [12].

For GaAs concentrator cells, V_{ocs} = 1050 mV under the temperature T = 300 K, thus $v_{oc} = 42 > 15$, FF_0 = 0.8894. Another condition is that $r_s < 0.4$, namely require $FF > 0.6FF_0 = 0.5336$, in fact, this condition can be reached easily for GaAs concentrator cells.

3 Characteristics Analysis

3.1 I-V Characteristics

The mathematical description of I-V characteristics for GaAs concentrator cells are represented by a nonlinear equation (6). Fig.2 shows the I-V characteristics of a GaAs concentrator cell at different laser light intensities from 10W/cm^2 to 100W/cm^2. The constant parameters for GaAs cells were set as 0.95 for the external QE, 0.8 for the fill factor, and 1.0 for the ideality factor. Three important operating points are short circuit current, open circuit voltage and Maximum Power Point. Maximum Power can be obtained by matching load resistance to GaAs cells characteristics. Fig.2 shows that GaAs cells output current is influenced by changing irradiance, whereas the output voltage is almost constant.

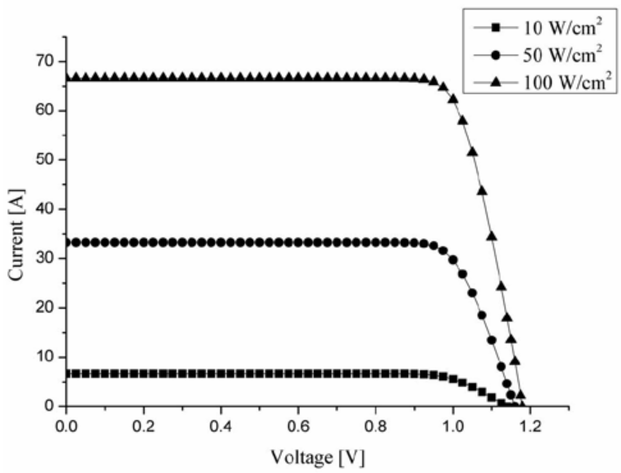

Fig.2 I-V characteristics of GaAs concentrator cells

3.2 Effects of Series Resistance

Series resistance is inherent in GaAs concentrator cells, and it mainly depends on the grid resistance and the contact resistance between semiconductors and electrodes. Once a high-intensity laser illuminates GaAs concentrator cells, a large current flows through the series resistance, thus there is a voltage dropdown proportional to the current. Fig.3 shows the series resistance of the GaAs concentrator cell for the 870 nm laser light. It is seen that the laser light intensity gets higher, the series resistance becomes smaller. For a high-intensity laser, this method calculated with the equation (9) is appropriate. But noting that, at low intensity, it does not give a precise value of series resistance due to the influence of the shunt resistance.

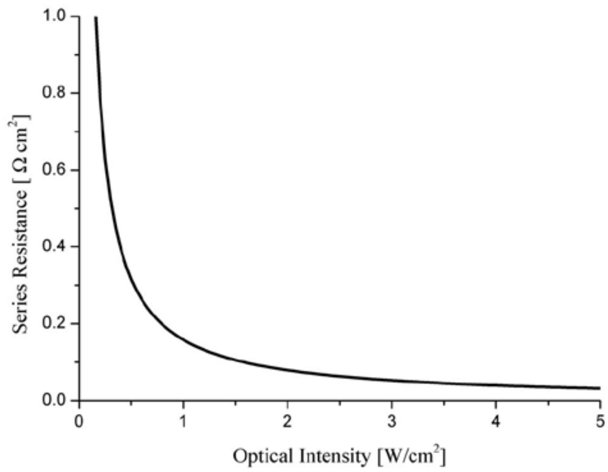

Fig.3 Calculated series resistance of GaAs concentrator cells

The conversion efficiency as a function of the series resistance for GaAs concentrator cells can be calculated with the equations (10-11). The constant parameters were set as 0.95 for the external QE, 1.0 for the ideality factor, and an 870 nm laser light with the intensity from 1W/cm^2 to 10W/cm^2. Fig.4 shows the calculated conversion efficiency. The optical intensity for solar light on the ground is as large as 0.1W/cm^2 at most. However, for laser light in the fiber optic powering easily reaches up to 10W/cm^2. A series resistance as large as 0.1–1Ω cm^2 serves to generate substantial solar power on the ground, while these series resistances may be too large to generate electricity for high-intensity laser. Therefore, it is necessary to significantly decrease the series resistance of GaAs concentrator cells, especially for high-intensity laser power transmission.

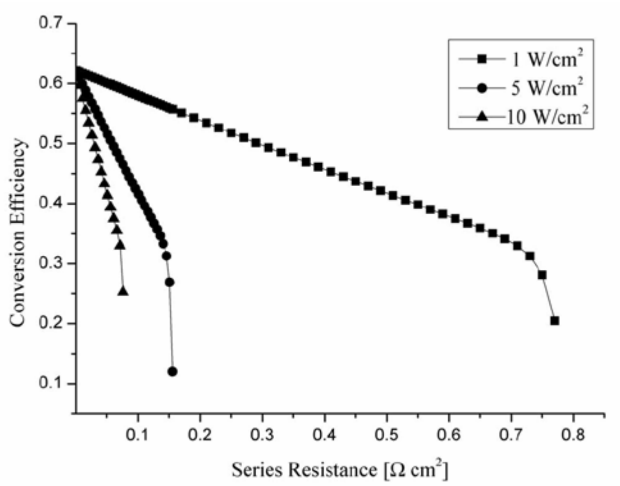

Fig.4 Conversion efficiency as a function of series resistance

3.3 Effects of Temperature

Temperature increase due to the illumination of a high power laser is one of the most important effect factors for GaAs concentrator cells photoelectric properties. Temperature increase inevitably degrades the conversion efficiency. To consider the relative importance of various GaAs cell parameters in determining the temperature dependency of P_m [11], the temperature dependencies are represented as:

$$\frac{1}{P_m}\frac{dP_m}{dT}=\frac{1}{I_{sc}}\frac{dI_{sc}}{dT}+\frac{1}{V_{oc}}\frac{dV_{oc}}{dT}+\frac{1}{FF}\frac{dFF}{dT} \qquad (12)$$

Five groups data for the temperature variation of P_m, V_{oc}, I_{sc}, and FF is shown in Table 1[11]. Considering terms of equation (12), the figures indicate that the term in V_{oc} is clearly the largest in magnitude. Hence, dP_m/dT is assumed to be most dependent on the temperature variation of V_{oc}.

Table 1 Temperature variation terms of GaAs cells

dP_m/dT [mW/cm^{2}K]	dV_{oc}/dT [mV/K]	dI_{sc}/dT [mA/cm^{2}K]	dFF/dT [Present/K]
-4.40×10^{-2}	-2.00	$+1.95\times10^{-2}$	-5.40×10^{-2}
-4.92×10^{-2}	-2.10	$+1.97\times10^{-2}$	-5.55×10^{-2}
-4.28×10^{-2}	-2.05	$+2.28\times10^{-2}$	-5.09×10^{-2}
-4.00×10^{-2}	-1.97	$+1.91\times10^{-2}$	-3.98×10^{-2}
-4.14×10^{-2}	-1.97	$+2.71\times10^{-2}$	-5.44×10^{-2}

The results of temperature dependency can be calculated using equations (3), (4) and (12), where $E_g(0)$ = 1.519eV, α=5.405×10^{-4} eV/K and β = 204 K. Typical temperature dependency runs for GaAs concentrator cells over a wide range of temperature are shown in Fig.5, noting that the terms in I_{sc} and FF are negligible. In general, over most of the temperature range, the conversion efficiency η and open circuit voltage V_{oc} decrease with increasing temperature, and there is a very good linearity between the open circuit voltage and the temperature. It is also seen that dP_m/dT is roughly proportional to dV_{oc}/dT for GaAs concentrator cells, and the spread in dP_m/dT values is mainly attributed to the variations in open circuit voltage. The spread in values indicates that great care should be exercised in applying published temperature dependency calculations to numerical predictions of GaAs concentrator cell performance in a given environment.

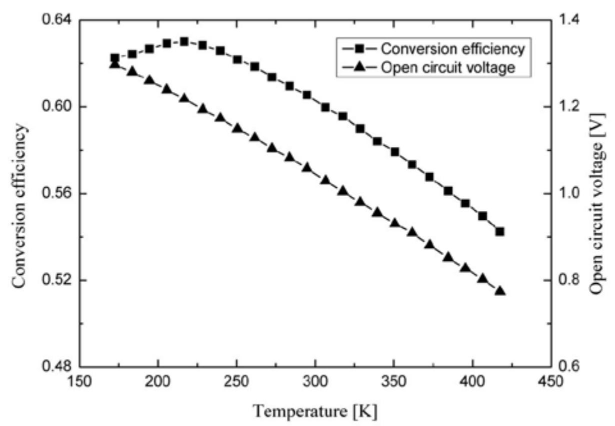

Fig.5 Variation of η and V_{oc} with temperature for GaAs cells

4 Conclusion

By analyzing the mathematical model, we clarified the characteristics of the GaAs concentrator cell for high-intensity laser. We analyzed the two important factors which inevitably degrade the conversion efficiency of GaAs cells. The first is series resistance of GaAs concentrator cells, and the second is temperature increase due to illumination of the high-intensity laser. From the calculation results, we found that there is a close relationship among the laser light intensity, the series resistance and the conversion efficiency. The laser light intensity increasing would decrease the series resistance, while the effect of series resistance for the conversion efficiency would become serious. In addition, the temperature effect on cells performance in a long range was studied. The conversion efficiency decreases with temperature increasing, which is mainly attributed to variations in the open circuit voltage. There is a very good linearity between the open circuit voltage and the temperature, and the conversion efficiency change rate is roughly proportional to the open circuit voltage change rate. Therefore, the extremely small series resistance and temperature control are important to obtain higher conversion efficiency for GaAs concentrator cells, especially under the high-intensity laser illumination.

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