Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Vacuum 77 (2005) 163–167
VACUUM
SURFACE ENGINEERING, SURFACE INSTRUMENTATION & VACUUM TECHNOLOGY
www.elsevier.com/locate/vacuum

Analysis of series resistance and *P–T* characteristics of the solar cell

Jinlei Ding*, Xiaofang Cheng, Tairan Fu

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, PR China

Received 2 July 2004; accepted 19 August 2004

Abstract

In this paper, based on the fact that the output power of a solar cell monotonically decreases with its temperature, we investigate the specific expression of the series resistance. Further, applying the specific expression of the series resistance, we analyze the relationship characteristics between the power and the temperature, and correspondingly present the operating temperature condition of the ideal maximal power.

Keywords: Solar cell; Series resistance; *P–T* characteristics

1. Introduction

The series resistance R_S of a solar cell is an important parameter that affects its efficiency. There are various methods for the measurement of such a resistance [1–6]. However, the theory expression of R_S is still unknown and has not been clearly disclosed in previous research. So the purpose of the paper is to present a method to determine the specific theory expression of the series resistance. Once we know the specific expression of R_S, we may obtain the characteristic curve of the output power with respect to its temperature of the solar cell, and get some significative conclusions.

2. Series resistance of the solar cell

At the steady state of *I–V* characteristics, the standard expression of the current density in the solar cell under the condition of a uniform illumination is generally described by [5]

$$I = m\phi - I_0(e^x - 1), \tag{1}$$

$$x = \frac{qI(R_L + R_S)}{AkT}, \tag{2}$$

where m is the photoelectric conversion factor, ϕ is the illumination intensity, I_0 is the reverse

*Corresponding author. Tel.: +8605513601646; fax: +8605513606459.
E-mail address: jlding@mail.ustc.edu.cn (J. Ding).

0042-207X/$ - see front matter
doi:10.1016/j.vacuum.2004.08.019

saturation current density, R_S is the series resistance, R_L is the load resistance, k is the Boltzmann constant, T is the absolute temperature, q is the elementary charge, and A is the diode ideal factor. And we define a new variable form

$$x_0 = \frac{qI_0(R_L + R_S)}{AkT}. \quad (3)$$

Generally, the output power of a solar cell is expressed by

$$P = I^2 R_L. \quad (4)$$

Taking the full differentials of Eqs. (1), (2) and (4), respectively, yields

$$\mathrm{d}I = m\,\mathrm{d}\phi - I_0 \mathrm{e}^x\,\mathrm{d}x, \quad (5)$$

$$\frac{\mathrm{d}x}{x} = \frac{\mathrm{d}I}{I} + \frac{\mathrm{d}R_L + \mathrm{d}R_S}{R_L + R_S} - \frac{\mathrm{d}T}{T}, \quad (6)$$

$$\mathrm{d}P = I^2\,\mathrm{d}R_L + 2IR_L\,\mathrm{d}I. \quad (7)$$

Combining Eqs. (5)–(7), we get the new full differential equation of the output power

$$\mathrm{d}P = I^2\left(1 - \frac{2R_L}{R_L + R_S} \times \frac{x_0\mathrm{e}^x}{1 + x_0\mathrm{e}^x}\right)\mathrm{d}R_L + 2IR_L\frac{m\,\mathrm{d}\phi}{1 + x_0\mathrm{e}^x} + 2I^2R_L\frac{x_0\mathrm{e}^x}{1 + x_0\mathrm{e}^x} \times \left(\frac{\mathrm{d}T}{T} - \frac{\mathrm{d}R_S}{R_L + R_S}\right). \quad (8)$$

Rewrite Eq. (8) as

$$\frac{\mathrm{d}P}{\mathrm{d}T} = I^2\left(1 - \frac{2R_L}{R_L + R_S}\frac{x_0\mathrm{e}^x}{1 + x_0e^x}\right)\frac{\mathrm{d}R_L}{\mathrm{d}T} + \frac{2IR_Lm}{1 + x_0\mathrm{e}^x}\frac{\mathrm{d}\phi}{\mathrm{d}T} + \frac{2I^2R_Lx_0\mathrm{e}^x}{1 + x_0\mathrm{e}^x} \times \left(\frac{1}{T} - \frac{1}{R_L + R_S}\frac{\mathrm{d}R_S}{\mathrm{d}T}\right). \quad (9)$$

In applications, it is a clear fact [7] that the output power P monotonically decreases with the temperature of the solar cell, that is,

$$\frac{\mathrm{d}P}{\mathrm{d}T} < 0. \quad (10)$$

There is an implicit condition in applications of Eq. (10) that is R_L and ϕ are constant with respect to the temperature T,

$$\frac{\mathrm{d}R_L}{\mathrm{d}T} = 0, \quad \frac{\mathrm{d}\phi}{\mathrm{d}T} = 0. \quad (11)$$

Hence, according to the condition of Eqs. (10) and (11), Eq. (9) may be simplified as

$$\left.\frac{\mathrm{d}P}{\mathrm{d}T}\right|_{R_L,\phi} = \frac{2I^2R_Lx_0\mathrm{e}^x}{1 + x_0\mathrm{e}^x}\frac{1}{T} - \frac{2I^2R_Lx_0\mathrm{e}^x}{(1 + x_0\mathrm{e}^x)(R_L + R_S)}\frac{\mathrm{d}R_S}{\mathrm{d}T} < 0. \quad (12)$$

Due to

$$2I^2R_L\frac{x_0\mathrm{e}^x}{1 + x_0\mathrm{e}^x}\frac{1}{T} > 0$$

R_S must be relevant to T. It means $\mathrm{d}R_S/\mathrm{d}T \neq 0$ must be satisfied. The analysis is significant to determine the specific theory expression of the series resistance.

As we know, there are only three types of thermal sensitive resistances [8]: conductor type, negative temperature coefficient type and positive temperature coefficient type. Consequently, the form of R_S, relevant to T, must belong to one of the above three types. In the following, we will discuss this issue in more detail, based on three types of thermal sensitive resistances.

Conductor type

$$R_S = R_0(1 + \alpha T), \quad (13)$$

where α is the conductor temperature coefficient ($\alpha > 0$) and R_0 is the condition resistance. We get

$$\frac{\mathrm{d}R_S}{\mathrm{d}T} = \alpha R_0 > 0,$$
$$\left.\frac{\mathrm{d}P}{\mathrm{d}T}\right|_{R_L,\phi} = \frac{2I^2R_Lx_0\mathrm{e}^x}{1 + x_0\mathrm{e}^x}\left(\frac{R_L + R_0}{R_L + R_S}\right)\frac{1}{T} > 0 \quad (14)$$

Eq. (14) contradicts the requirement of Eq. (12), so R_S does not belong to the conductor type.

Negative temperature coefficient type

$$R_S = R_0\mathrm{e}^{B/T}, \quad (15)$$

where B is the semiconductor material coefficient ($B>0$) and R_0 is the condition resistance. We get

$$\frac{\mathrm{d}R_S}{\mathrm{d}T} = -\frac{BR_S}{T^2} < 0,$$

$$\left.\frac{\mathrm{d}P}{\mathrm{d}T}\right|_{R_L,\phi} = \frac{2I^2R_Lx_0\mathrm{e}^x}{1+x_0\mathrm{e}^x}\left[\frac{1}{T} + \frac{BR_S}{(R_L+R_S)T^2}\right] > 0. \tag{16}$$

It is obvious that Eq. (16) contradicts the requirement of Eq. (12). Hence, R_S also does not belong to the negative temperature coefficient type.

Positive temperature coefficient type

$$R_S = R_0\mathrm{e}^{BT}, \tag{17}$$

where B is the semiconductor material coefficient ($B>0$) and R_0 is the condition resistance. We get

$$\frac{\mathrm{d}R_S}{\mathrm{d}T} = BR_S > 0,$$

$$\left.\frac{\mathrm{d}P}{\mathrm{d}T}\right|_{R_L,\phi} = \frac{2I^2R_Lx_0\mathrm{e}^x}{1+x_0\mathrm{e}^x}\left[\frac{1}{T} - \frac{BR_S}{(R_L+R_S)}\right]. \tag{18}$$

In Eq. (18), to satisfy $\mathrm{d}P/\mathrm{d}T|_{R_L,\phi} < 0$ of Eq. (9), the condition is required that

$$B > \left(1 + \frac{R_L}{R_S}\right)\frac{1}{T} > 0. \tag{19}$$

It accords with the definition of the semiconductor material coefficient $B>0$. Therefore, the series resistance R_S may be the specific form of the positive temperature coefficient type constricted by Eq. (19). This conclusion allows the expression of the series resistance of solar cell to be clarified in some specific form. We may verify this form by experimental data of the series resistance. Fig. 1 shows the *I–V* characteristic of the solar cell under different operating temperatures [7].

The numerical value of R_S may be derived from *I–V* characteristics at a certain temperature [6],

$$R_S = \frac{1}{\lambda}\frac{1}{I_2 - I_1}\ln\left[\frac{I_{ph} - I_2}{I_{ph} - I_1}\right] - \left(\frac{V_2 - V_1}{I_2 - I_1}\right), \tag{20}$$

where I_{ph} is light generated current density and I_1, I_2, V_1, V_2 are the current densities and the voltages of any two points at some *I–V* curve. The calculated R_S values are shown in Table 1.

Further we fit the numerical values of R_S using the theory expression of Eq. (17); the result is shown in Fig. 2. It is obvious that the theory expression of R_S can accurately accord with experimental data, with a high fitting relativity of 0.99266.

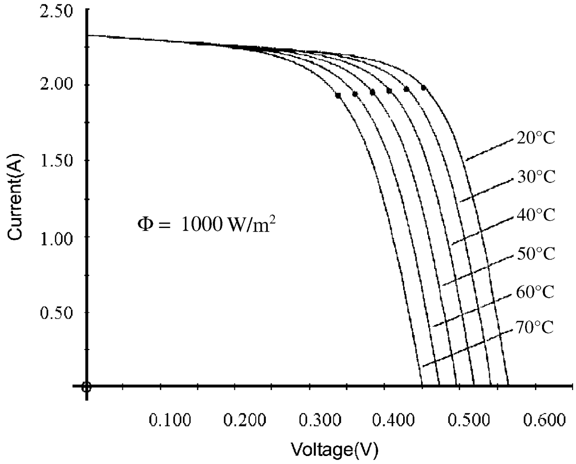

Fig. 1. *I–V* characteristics for a silicon solar cell at different temperatures, $A = 1.49$, $I_{ph} = 2.33A$.

As we all know, the physical structure of series resistance of the solar cell is complicated, with relevance to base contact resistance, base bulk resistance, sheet resistance of the top (emitter) layer, metallic resistance of the emitter layer and metallic resistance of the electrodes [9]. However, Eq. (17) is a synthetic theory expression based on these factors, and may conveniently predict the values of R_S instead of experimental data obtained by traditional complicated measurements. The establishment of the theory expression of the series resistance is very significant in applications of the solar cell.

3. *P–T* characteristics of the solar cell: power distribution with respect to temperature

In this section, adopting the above theory expression of series resistance, we will investigate the relationship between the power and the temperature of the solar cell, and present the operating temperature condition of the ideal maximal power.

Table 1
Experimental and calculated data of the silicon solar cell

T (K)	293	303	313	323	333	343
V_1 (mV)	0.452	0.427	0.401	0.376	0.352	0.325
V_2 (mV)	0.501	0.477	0.453	0.430	0.408	0.383
I_1 (A)	2.00	2.00	2.00	2.00	2.00	2.00
I_2 (A)	1.50	1.50	1.50	1.50	1.50	1.50
R_S (Ω)	0.02754	0.02817	0.02980	0.03143	0.03306	0.03469

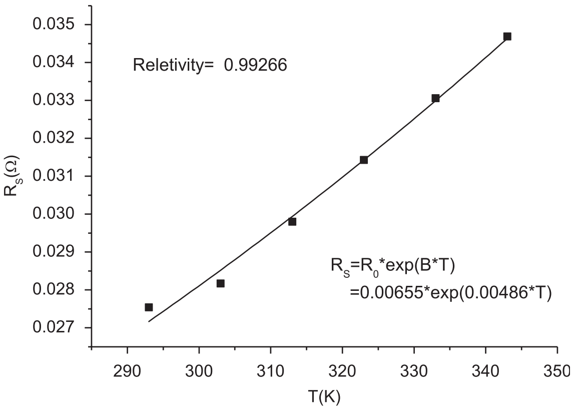

Fig. 2. Exponential fitting curve of the silicon solar cell series resistances.

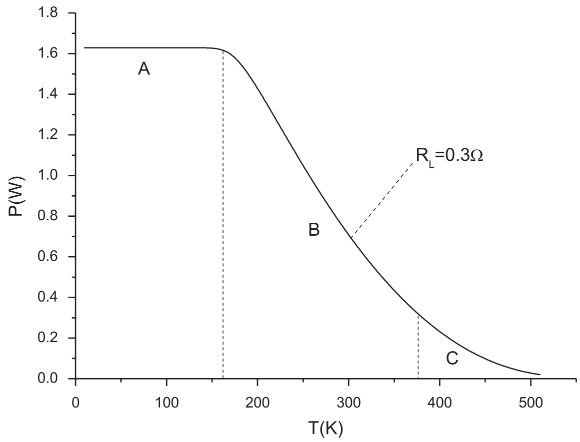

Fig. 3. P–T characteristics of the silicon solar cell.

The investigated experimental conditions are the same to those of Section 2; that is, we choose the same solar cell, $R_S = 0.0065\ \exp(0.00486T)$, $A = 1.49$, $I_{ph} = 2.33$A. Other experimental parameters are $R_L = 0.3\,\Omega$, $\phi = 1000\,\mathrm{W}/\mathrm{m}^2$. Through calculations at different operating temperatures, we get the characteristics of the output power with respect to the temperature under the given illumination and load resistance, as shown in Fig. 3. The P–T characteristics are firstly obtained by theory analysis, not by experiment measurements, and have not been reported yet in previous literatures.

The curve in Fig. 3 may be divided into three bands: A, B, C bands.

(1) A band with the ideal maximum power distribution: with the decrease of the temperature of the solar cell, the output power of the solar cell reaches its ideal maximum, a constant. Based on [10], the smaller the temperature is, the closer the current density I increases to the short-circuit current I_{SC}. Hence, in band A, the fact that the temperature is low enough makes I reach the maximum value I_{SC}. It means the output power is maximal in the operating temperature range restricted by band A.
(2) B band: in this operating temperature range, the output power monotonically decreases along with the temperature, which is widely observed in practice [7]. Generally, the solar cell works in the range.
(3) C band: comparing with the characteristics of the B band, here, the output power exponentially decreases with the temperature. Once the temperature is high enough, the output power achieves the minimum, close to zero.

Additionally, we also plot the P–T characteristics of the solar cell under different load

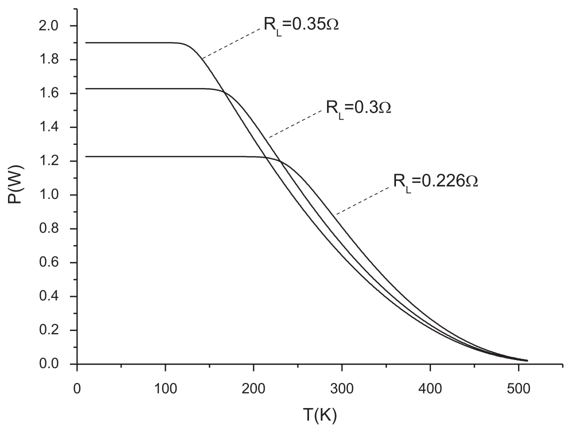

Fig. 4. *P–T* characteristics of the silicon solar cell where the load resistance varied.

resistances $R_L = 0.226\,\Omega$, $R_L = 0.3\,\Omega$, $R_L = 0.35\,\Omega$ (shown in Fig. 4).

It is obvious that the larger R_L becomes, the lower the operating temperature under which the output power reaches the ideal maximum.

4. Conclusion

(1) Based on the fact that the power decreases along with the temperature of the solar cell, this paper presents a simple and effective theory expression of the series resistance.

(2) The $P - T$ characteristic curve of the solar cell is theoretically given not depending on experimental measurements. Definituding the relationship between the power and the temperature is significative to effectively utilize the solar cell.

References

[1] Wolf M, Rauschenbach H. Adv Energy Conversion 1963;3:455.
[2] Rauschen bach H. Solar cell array design handbook. New York: Van Nostrand Reinhold Company; 1980. p. 56.
[3] Imamura Ms. porscheller. Proceedings of the eighth photovoltaic specialists conference. New York: IEEE; 1970. p. 102.
[4] Agarwal SK, Muralidharan R, Agarwal A, Teway VK, Jain SCJ. Phys D 1981;14:1643.
[5] Singh VN, Singh RP. J Phys D 1983;10:1823–5.
[6] EL-Adwi MK, Al-Nuaim IA. A method to determine the solar cell series resistance from a single *I–V*. Characteristic curve considering its shunt resistance—new approach 2002;64:33–6.
[7] Shijie Yu, Ruohui He. Photovoltatic using of solar energy. Hefei: Hefei University of Technology; 1991. p. 11–17.
[8] Kaixian Xu, Jimin Ye. Thermal sensitive resistor. Beijin: China Machine Press; 1981. p. 1–4.
[9] Dadu M, Kapoor A, Tripathi KN. Effect of operating current dependent series resistance on the fill factor of a solar cell. Sol Energy Mater Sol Cells 2002;71:213–8.
[10] Enke Liu. Photronic cell and its application. Beijin: Science Press; 1989. p. 103.