Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp353-354

G-6-03

Transient Thermal Analysis of Si-based Solar Cell Using Electrical Junction-Temperature Measurement and Impedance Spectroscopy

Yu-Hsueh Chin[1], Shui-Jinn Wang[*1,2], Chien-Hsiung Hung[1], Ya-Chi Huang[1], Chien-Hung Wu[3], Nai-Sheng Wu[1], and Hao-Ping Yan[1]

[1]Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan.
[2]Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, Taiwan.
[3] Department of Electronics Engineering, Chung Hua University, Hsinchu, Taiwan.
*Phone: +886-6-2757575-62351, Fax: +886-6-2763882, E-mail: sjwang@mail.ncku.edu.tw

Abstract

Transient thermal responses of solar cells (SCs) subjected to fluctuations in sun light intensity and ambient temperature is studied. A closed form of the open-circuit voltage (V_{OC}) as a function of junction temperature (T_j) is presented, which is used to monitor the junction temperature at transient and steady-state periods with a good accuracy. In addition, based on the thermal response of the SC through the extraction of junction temperature from measured V_{OC} data, a simple thermal equivalent circuit is proposed. Temperature-dependent parasitic parameters of SCs including R_S and R_{Sh} as well as thermal resistance and capacitance are extracted and discussed.

1. Introduction

With the greenhouse effect becoming worse, the pace of global warming seems having an increasing speed nowadays. The increase in ambient temperature (T_a) is a critical issue to both eco-environment and technology applications, especially for the energy conversion of solar cells (SCs). Attributing to poor efficiency and self-heating caused by parasitic resistances during solar energy conversion, the junction temperature (T_j) of SCs could be several tens degrees in centigrade higher than the ambient temperature. A much higher temperature can be find from the worst case of open-circuit condition of SCs used in high concentration photovoltaics.

In essential, elevated temperature leads to efficiency drop of SCs for the decrease in the open-circuit voltage (V_{OC}) and fill factor (FF) [1]. To clarify the thermal effect on the performance of SCs, in addition to the investigation of the temperature dependent electrical parameters such as V_{OC}, FF, short-circuit current (J_{SC}), etc., an accurate mean to monitor the true solar cell junction temperature measurement is also important.

In this study, the experimental data of V_{OC} at a designed set of temperatures were used to reveal the junction temperature of SCs. Upon sunlight irradiation and fluctuations in ambient temperature, both transient and steady states of T_j of SCs were analyzed. A transient thermal equivalent circuit and a simple equation to model the temperature dependent V_{OC} were proposed. Comparisons between the theoretical and experimental results were made. Extraction of parasitic resistances based on measured J-V curves and impedance spectroscopy (IS) with sunlight irradiation at different temperatures was also presented and discussed.

2. Theoretical basis

Dependence of V_{oc} on T_j

Using the general *V-J* characteristics of SCs under steady-state illumination, V_{OC} is written as [1-2]

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{J_{SC}}{J_0}\right) \quad (1)$$

$$J_0 = CT^{(3+\gamma/2)}\exp[-E_g(T)/kT] \quad (2)$$

where J_0 is the reverse saturation current in dark and γ (≈-1.2) is a parameter related to minority carrier diffusion length [3-4]. Note that for the SCs under steady-state illumination condition, the temperature T could be referred to T_j. Following the general $E_g(T)$ model [5], an expression for the temperature dependent $V_{OC}(T)$ can be expressed as

$$E_g(T) = E_g(0) - \alpha T^2/(T+\beta) \quad (3)$$

$$V_{OC} = \frac{-kT}{q}\left(3+\frac{\gamma}{2}\right)\ln(T) + \frac{E_g(0)}{q} + \frac{\alpha\beta T}{q(T+\beta)} + c^*T \quad (4)$$

where c^* is a constant depends on structure, material quality, and light intensity. It is noted that the accuracy of eq. (4) has been confirmed from a close fit to experimental V_{OC}-T_j data [6-7] with a fiting error < 0.59-2.59%. Here, eq. (4) will be employed for the extraction of T_j from the measured V_{oc} in this study.

Thermal resistance and transient model of solar cells

The thermal resistance (θ_{th}) of SCs, as expressed as eq. (5), is determined by the ratio of ΔT and P_d, where ΔT is the temperature difference between T_j and T_C, P_d is the absorbed power without conversion for the SCs under sunlight irradiation.

$$\theta_{th} = \frac{\Delta T}{P_d} = \frac{T_j - T_C}{[1-(\sum_{i=300}^{i=2500} R_i E_i \Delta\lambda_i / P_{in}) - \eta_{\max}]\times A \times P_{in}} \quad (5)$$

where $\sum_{i=300}^{i=2500} R_i E_i \Delta\lambda_i$ is the reflective loss (P_{ref}) of solar cell for solar spectrum in the range of 300-2500 nm [8], T_C is temperature of case of SCs, and the other symbols bear the usual meanings. The transient thermal equivalent circuit is shown in Fig 1. On the basis of Newton's law of cooling, the T_j-t waveform of the SCs upon sunlight irradiation at $T_j(0)$ can be expressed as

$$T_j(t) = \Delta T(t) + T_C = T_\infty + (T_0 - T_\infty)e^{-\frac{t}{\tau_{th}}} \quad (6)$$

where τ_{th} (=$\Theta_{th}C_{th}$) and C_{th} are the thermal time constant and the thermal capacitance, respectively.

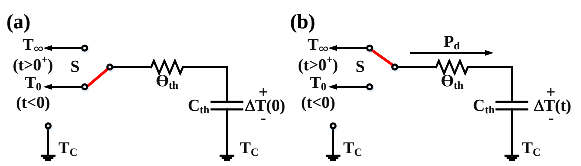

Fig. 1 The transient thermal equivalent circuit (a) before T_j(t<0) (b) after T_j(t>0$^+$) illumination of SCs.

3. Experiments

Solar cells used in this study were with an n$^+$-p structure (3.4 × 2.1 cm^2 and 200 μm thick) and mounted on a temperature controlling plate. Illuminated J-V, P-V curve, and IS analysis of SCs were all measured under AM1.5G at temperature varying from 40 to 80 °C at an interval of 10 °C to determine cell parameters including V_{OC}, FF, η_{max}, shunt resistance (R_{Sh}), series resistance (R_S), and IS parameters.

The IS experiments were made under a dc bias of 0.35 V and an ac voltage of 5 mV in rms with the frequency ranging from 0.1 to 20 kHz. The reflectivity of SCs was measured in the solar spectrum of 300-2500 nm. The time interval for the transient V_{OC} measurements is 16.7 ms for two neighboring data points. Infrared (IR) thermometer, and thermocouple were used to monitor the cell temperature.

4. Results, and discussion

Figs. 2(a) and (b) show the experimental J-V and P-V curves of SCs under different temperatures. Fig. 2(c) shows the extracted electrical parameters of SCs based on Figs. 2(a) and (b). Fig. 3(a) shows the ac equivalent circuit of SCs [9]. Fig. 3(b) and (c) show the cole-cole plots obtained from IS measurements and the corresponding ac parameters of SC shown in Fig. 3(a), respectively.

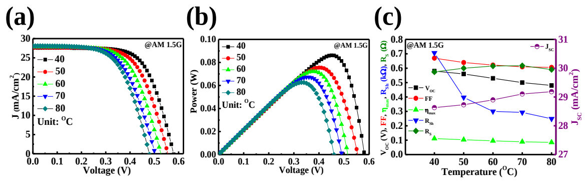

Fig. 2 (a) the measured J-V curves, (b) P-V curves (c) the extracted V_{OC}, J_{SC}, FF, η_{max}, R_{Sh}, and R_S of SCs as a funciton of temperature.

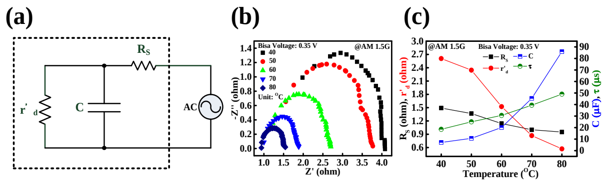

Fig. 3 (a) ac equivalent circuit [9], (b) Cole-cole plots, and (c) R_S, r'_d, C, and τ of SCs at AM 1.5G under temperature from 40 to 80 °C.

Figs. 4(a) and (b) show the solar spectrum of AM 1.5G, reflective loss, reflectivity, and heat flux components of SCs, respectively. The extracted SCs steady-state thermal resistance parameters are shown in Table 1.

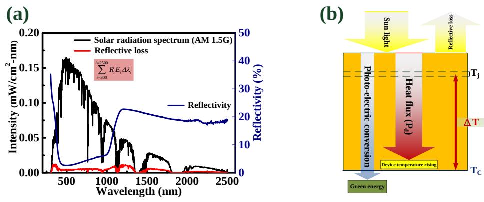

Fig. 4 (a) Solar spectrum of AM 1.5G, reflective solar spectrum, and reflectivity of SCs (b) The schematic diagram to show the heat flux components of SCs.

Table 1. Experimental data of steady-state thermal resistance of SCs.

T_C (°C)	T_j (°C)	ΔT (°C)	Area (cm²)	P_{in} (W/cm²)	P_{ref} (W/cm²)	η_{max} (%)	P_d (W)	Θ_{th} (°C/W)
23.50	28.91	5.41	7.14	0.1	0.00803	10.5	0.70	7.72
V_{OC} (V)	V_{OC} (V)							
0.609	0.597							

Fig. 5(a) shows the measured V_{OC} and η_{max} as a function of T_j. Obviously, the temperatures measured by both IR thermometer and thermocouple are only reflect the surface temperature of the SCs under test, which could be very different from that of the "real" T_j derived from eq. (4). According to the derived V_{OC}-T_j curves, the measured transient V_{OC} waveforms were converted to transient T_j waveforms. Fig. 5(b) shows both the transient waveforms of V_{OC} and the transient T_j waveforms at different ambient temperatures. Based on the transient T_j waveforms, both τ_{th} and C_{th} were derived and listed in Table 2, respectively.

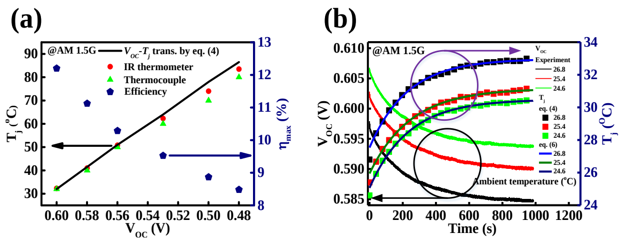

Fig. 5 (a) V_{OC}, η_{max}, and T_j using eq. (4), IR thermometer, and thermocoucple of SCs (b) Experimental transient-state of V_{OC}, transient temperature, and transient thermal model fitting of SCs under different ambient temperature (26.8, 25.4, and 24.6 °C, respectively).

Table 2. Extracted data of τ_{th}, Θ_{th}, and C_{th} using thermal T_j waveform shown in Fig. 5(b).

T_c (°C)	T_0 (°C)	T_∞ (°C)	τ_{th} (s)	Θ_{th} (°C/W)	C_{th} (W-s/°C)
26.80	27.53	32.97	228.63	9.40	24.32
25.40	25.95	31.16	252.30	8.77	28.54
24.60	25.06	30.49	237.12	8.97	26.43

4. Conclusion

The J-V characteristics of SCs under AM 1.5G at different temperatures have been investigated. A closed form of V_{OC} as a function T_j has been derived which shows a high accuracy to experimental data. Transient and stable junction temperature of SCs upon sunlight irradiation and different ambient temperature has been monitored through V_{OC} measurement. A simple thermal equivalent circuit with temperature-dependent thermal resistance and thermal capacitance has been proposed to model the thermal response of SCs with confirmed accuracy. In addition, temperature-dependent parasitic parameters of SCs including R_S and R_{Sh} (r'_d) have been extracted from J-V curves and IS analysis. It is expected that the study of thermal response of SCs to fluctuations in sun light intensity and ambient temperature in the present work could be useful for understanding and improving the thermal behaviors of SCs for high concentration photovoltaics.

Acknowledgement:

This work was supported by the Ministry of Science and Technology (MOST), Taiwan, under contract No. NSC 104-2221-E-006-130-MY3 and MOST 104-2221-E-006-066.

References

[1] *M. A. Green, Solar cells: operating principles, technology, and system applications,* (2009).
[2] *K. Nishioka et al., Sol. Energy Mater. Sol. Cells*, **90** (2006) 62.
[3] *J. Batista et al., Appl. Phys. Lett.* **82** (2003) 4077.
[4] *P. C. Mathur et al., J. Appl. Phys.*, **52** (1981) 3651.
[5] *J. Singh, Electronic and optoelectronic properties of semiconductor structures,* (2003) 517.
[6] *B. J. Huang et al., Sol. energy*, **85** (2011) 388.
[7] *P. Singh et al., Sol. Energy Mater. Sol. Cells*, **92** (2008) 1611.
[8] *ASTM, G173-03*, (2012) 15.
[9] *Ivàn Mora-Seró et al., Energy Environ. Sci.*, **2** (2009) 678.