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# Photocarrier Radiometry for Noncontact Evaluation of Monocrystalline Silicon (c-Si) Solar Cell Irradiated by 1 MeV Electron Beams

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**Abstract** In this paper, the monocrystalline silicon (c-Si) solar cell irradiated by 1 MeV electron beams was investigated using noncontact photocarrier radiometry (PCR). A theoretical 1D two-layer PCR model including the impedance effect of the p-n junction was used to characterize the transport properties (carrier lifetime, diffusion coefficient, and surface recombination velocities) of c-Si solar cells irradiated by 1 MeV electron beams with different fluences. The carrier transport parameters were derived by the best fit through PCR measurements. Furthermore, an $E_{\mathrm{v}} + 0.56$ eV trap was introduced into the band gap based on the minority carrier lifetime reduction. An I–V characteristic was obtained by both AFORS-HET simulation and experimental study, and the simulation results shows in good agreement with the experimental results. Moreover, the simulation and experiment results also indicate that the increase of fluences of electron beams results in the reduction of short-circuit current and open-circuit voltage.

**Keywords** Electron irradiation · Photocarrier radiometry · Silicon solar cell

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# 1 Introduction

Photocarrier radiometry (PCR), due to its high resolution and good sensitivity, has been developed as a noncontact technology to evaluate optoelectronic parameters of semiconductor materials (i.e., silicon wafers) [1,2] and photovoltaic devices [3–8]. Generally, the monocrystalline silicon (c-Si) solar cell has been widely applied in the near-earth mission satellites which are inevitably irradiated by charged particles (mainly protons and electrons) in space leading to the degradation of its performance [9]. Equivalent fluence method (EFM) is recognized as an international and popular methodology for evaluation and prediction of the performance of solar cells on orbit. Under the instruction of EFM, solar cells irradiated by 1 MeV electrons or 10 MeV protons with different fluences are employed to extract the relative damage coefficient. Besides, the electron fluence at 1 MeV energy on the near-earth orbit is relatively larger than the higher energy ones [10]. Additionally, the performance of solar cells is determined by the carrier transport properties (i.e., minority carrier lifetime $\tau$, diffusion coefficient $D$, surface recombination velocities$S$). In this work, the carrier transport properties (especially minority carrier lifetime) of the c-Si solar cells irradiated by different fluences using PCR was studied, the I–V characteristics using the carrier lifetime obtained by PCR was simulated and the performance degradation of c-Si solar cell by comparing open-circuit voltage ($V_{\text{oc}}$), and short-circuit current ($I_{\text{sc}}$) with the nonirradiated one was evaluated at the end of this work.

# 2 Experimental Apparatus and Procedures

## 2.1 Specimens

In this case of investigation, three c-Si solar cells were irradiated by electron beams at the energy of 1 MeV with fluences of $1 \times 10^{14}$, $1 \times 10^{15}$, and $1 \times 10^{16}\text{e}^{-}\text{cm}^{-2}$, respectively, which were performed using an electron accelerator (ELV-8) and one nonirradiation c-Si solar cell is used for comparison analysis. The detailed information of this kind of solar cell is shown in Fig. 1a, b.

## 2.2 Description of Experimental Technique

### *2.2.1 Principle of Technique*

The PCR signal is obtained by solving the carrier transport equation and integrating the carrier density wave (CDW) over the thickness of the solar cell. For a typical p-n junction device, it consists of $p$-($n$-)-type quasi-neutral region (QNR) and the space charge region (SCR). In this work, the photovoltaic device geometry is an abrupt p-n junction fabricated on a long-base $p$-type substrate wafer (base) by diffusion of $n$-type impurity to form a thin $n$-type surface layer (emitter) assumed. The finite width of the SCR at the junction is neglected. By taking the junction and diffusion capacitance and bias voltage of p-n junction of solar cell into account, the carrier density wave and the

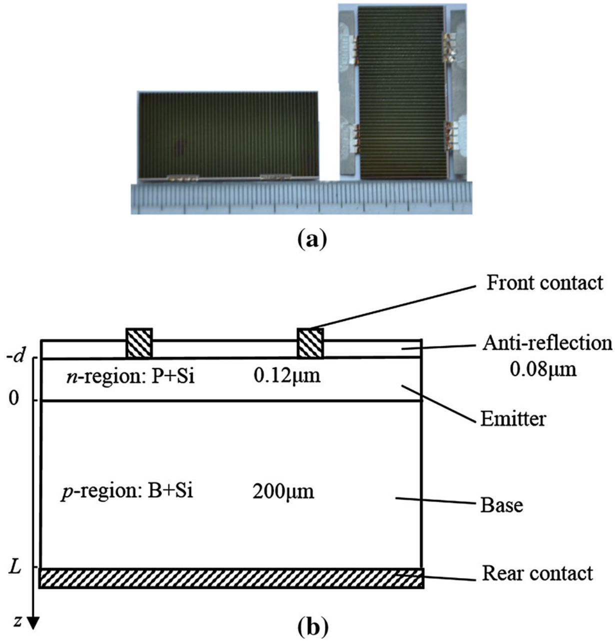


**Fig. 1** A c-Si solar cell specimen: (a) the size and (b) the layer structure of this specimen

boundary value problem are given in detail by Reference [8]. The PCR signal can be expressed as follows:

$$S_{\mathrm{PCR}}(\omega) \approx F(\lambda_1, \lambda_2)\left(\int_{-d}^{0} \Delta p(z,\omega)\mathrm{d}z + \int_{0}^{L} \Delta n(z,\omega)\mathrm{d}z\right), \tag{1}$$

where $(\lambda_1, \lambda_2)$ is the spectral bandwidth of the infrared detector, $F(\lambda_1, \lambda_2)$ denotes the proportional factor, $\Delta p(z,\omega)$ and $\Delta n(z,\omega)$ are excess carrier density wave of emitter(thickness, $d$) and base (thickness, $L$) region, respectively.

### *2.2.2 Apparatus*

The PCR experimental system has been described elsewhere [6,8]. An 808 nm diode laser internally modulated using the voltage output of a function generator is employed as a carrier excitation source. The laser beam is focused on the solar cell surface coincident with the focal point of an off-axis parabolic mirror that is used to collect a portion of photons. The collected light is focused on an InGaAs detector (Throlabs PDA10CS) and its frequency response is up to 17 MHz. The detector has a spectral bandwidth of 800–1700 nm and an active element with the area of 0.79 $\mathrm{mm}^2$. A long-pass filter LP-1000 nm is placed in the front of the detector and used to block the excitation laser beam from this detector. The signal from the detector is demodulated by a lock-in amplifier (SR830, Stanford). All instruments and data acquisition are

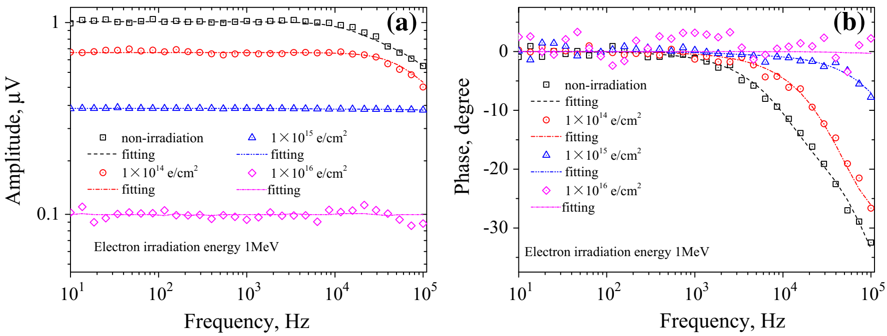


**Fig. 2** Amplitude and phase of PCR signals obtained by experiment and best-fitting: (a) amplitude–frequency response, (b) phase–frequency response

controlled using in-house developed software. PCR frequency scan measurements from 10 Hz to 100 KHz with a focused laser beam were carried out at room temperature by a sinusoidally modulated intensity. The spot size on the c-Si solar cell and the output power of the laser are about 400 μm and 32 mW, respectively.

## 3 Results

The amplitude and phase of PCR signal of the c-Si solar cell before and after electron irradiation are illustrated in Fig. 2. From Fig. 2, it can be seen that the signals of 1 MeV electron irradiation ones are heavily changed in comparison with the nonirradiation one due to the concentration of new traps introduced by electron irradiation which would capture the minority carriers [11]. According to Reference [8], electrons at 1 MeV can totally go through the entire specimen, and then the traps induced by electron irradiation damage will affect the carrier transport properties throughout the cell.

In the previous work [8], the carrier transport parameters had been extracted from the two PCR channels (amplitude and phase), and the reliability and precision measurement of the associated parameters were investigated by two independent multi-parameters best-fitting computational programs (labeled as "Mean-value best fit (MV best fit)" and "statistic fit"). To estimate the carrier transport properties of c-Si solar cell in this work, both the amplitude and phase of the PCR signal were fitted to the foregoing theoretical model, Eq. 1.The fitting results are presented in Table 1. In this work, the lifetime, which is related to the concentration of traps ($N_{\mathrm{D}}$), is employed to calculate the I–V characteristic using AFORS-HET developed by Helmholtz-Zentrum Berlin [12]. The lifetime, $\tau$, of these four specimens are 2.65 μs, 1.58 μs, 0.34 μs, and 0.038 μs (less than or equal), respectively. Then the concentration of the deep level trap ($E_{\mathrm{V}}$+0.56 eV, acceptor-like, which is a typical kind of traps brought by electron according to Reference [9]) in p region is defined by

$$N_{\mathrm{D}} \approx \frac{1}{\tau V_{\mathrm{T}} C_{\mathrm{T}}}, \tag{2}$$

**Table 1** Best-fitted transport parameters in p region of solar cells irradiated by 1 MeV electron beams

| Fluence($e^-/cm^2$) | Carrier lifetime ($\mu s$) | | diffusivity ($cm^2/s$) | | SRV ($m\ s^{-1}$) | |
|---|---|---|---|---|---|---|
| | MV best fit | Statistic fit | MV best fit | Statistic fit | MV best fit | Statistic fit |
| - | 2.65 | $2.95 \pm 1.26$ | 18.7 | $21.8 \pm 13.0$ | 0.99 | $1.10 \pm 0.47$ |
| $1 \times 10^{14}$ | 1.58 | $1.83 \pm 0.46$ | 18.6 | $17.48 \pm 12.0$ | 0.99 | $1.00 \pm 0.35$ |
| $1 \times 10^{15}$ | 0.34 | $0.35 \pm 0.08$ | 19.1 | $19.3 \pm 11.0$ | 0.99 | $1.16 \pm 0.73$ |
| $1 \times 10^{16}$ | 0.038 | $0.034 \pm 0.022$ | 21.1 | $19.9 \pm 11.0$ | 0.99 | $1.10 \pm 0.62$ |

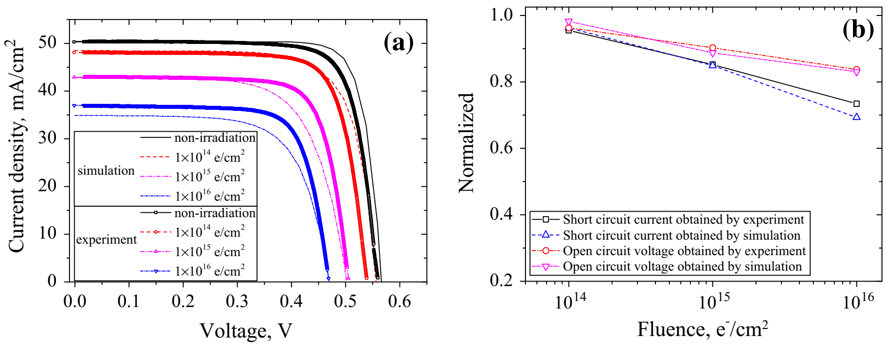


**Fig. 3** The simulation and the experiment result of different electron fluences (a) Simulated and experimental I–V characteristics (b) Comparison of normalized $I_{sc}$ and $V_{oc}$

where $V_T$ is the thermal velocity and $C_T$ (cm $s^{-1}$) is the thermal capture cross section ($cm^2$) for carrier, respectively.

Simulation characteristic in combination with experiment and the normalized $I_{sc}$ and $V_{oc}$ of c-Si solar cells before and after irradiation with different fluences are shown in Fig. 3, respectively, and a good agreement is found between simulation and experiment. Fig. 3 shows that the $I_{sc}$ and $V_{oc}$ decrease as the fluence increases.

## 4 Conclusion

A theoretical 1D two-layer PCR model including the impedance effect of p-n junction was used to characterize the transport properties (carrier lifetime, diffusion coefficient, and two surface recombination velocities) of c-Si solar cells irradiated by 1 MeV electron beams. Experimental investigations using PCR on c-Si solar cells irradiated by different fluences of electron beams were presented. Besides, the PCR signal was heavily changed due to different fluence of electron at 1 MeV. The carrier transport parameters were obtained by best fitting the PCR experimental results. Additionally, an I–V characteristic was simulated by the introduction of a kind of typical irradiation trap according to the minority carrier lifetime reduction from PCR measurements. The simulation of I–V characteristic shows in good agreement with the experimental results. The result indicates that the increase of electron fluence caused the decrease of short-circuit current and open-circuit voltage due to the reduction of minority carrier lifetime.

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