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ScienceDirect
Solar Energy 83 (2009) 1446–1453
SOLAR ENERGY
www.elsevier.com/locate/solener

The circuit point of view of the temperature dependent open circuit voltage decay of the solar cell

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Received 2 November 2008; received in revised form 5 March 2009; accepted 9 March 2009
Available online 7 April 2009

Communicated by: Associate Editor Takhir Razykov

Abstract

The open circuit voltage decay (OCVD) technique has been used to determine the minority carrier lifetime. In this study, an experimental and analytical method is described for determination of minority carrier lifetime at porous Si based solar cell by photo induced OCVD technique. The cell is illuminated by a monochromatic light source ($\lambda = 658$ nm) in the open circuit configuration, and the decay of voltage is measured after abruptly terminating the excitation. For the analysis of the OCVD characteristic of solar cell device, equivalent electrical circuit has been proposed in which the diffusion capacitance is connected in series with the contribution of the solar cell interface. Exact minority carrier lifetimes at low (50–170 K) and high (190–330 K) temperature regions have been obtained as 28.9 and 2.65 μs from the temperature dependent OCVD measurements by using an alternative extraction technique.

Keywords: Minority carrier lifetime; Porous Si based solar cell; Open circuit voltage decay technique; Circuit level simulation

1. Introduction

In some works, photovoltaic properties (such as wavelength depended photosensitivity, internal quantum efficiency, illuminated and dark *I–V* measurements) of porous Si based solar cell structures have been extensively studied and reported in the literature (Rabha et al., 2008; Badawy, 2008). Porous silicon is increasingly applied to the fabrication of photovoltaic devices as a low-cost material (Smestad et al., 1992). Porous Si based solar cells are influenced by the electronic properties of interface. Various reports have been made to correlate these properties with the solar cell performance (Badawy, 2008; Bisi et al., 2000). The most important advantage of using porous Si in solar cells is its band gap and large minority carrier lifetime. In addition, this device is attractive because of the feasibility for fabricating low cost–low temperature fabrication process for fast photo diodes having response times of $\leqslant 50$ μs.

The minority carrier lifetime, eminent parameter influencing the performance of a solar cell, is often measured with the transient methods. The minority carrier lifetime in Si based device was obtained by OCVD and short-circuit decay techniques have been noted by several groups (Deshmukh and Nagaraju, 2005; Stutenbaeumer and Lewetegn 2000). OCVD technique, relatively facile, is frequently used for estimation effective minority carrier lifetime in the solar cells. In particular, evaluation of open circuit voltage versus temperature data provides valuable information about the main recombination route in the devices (Rau and Schock, 1999). Until now, there could not be found any theoretical model about the temperature depended effective minority carrier lifetime extraction technique by using equivalent circuit approximation. The observed temperature depended effective minority carrier lifetime behavior

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0038-092X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2009.03.009

in this study, cannot be explained by existence model in literature (Hsieh and Card, 1984). It thus became necessary to construct alternative theoretical approximation. We proposed a procedure to extract effective carrier lifetime of the devices. The presented theoretical results explain the role of equivalent circuits in time dependent open circuit transient characteristic of the investigated solar cell.

OCVD characteristics of solar cells are customarily described by an equivalent circuit model, which includes series resistance, diode dynamic resistance and capacitance. Dynamic resistance and capacitance values are modulated by temperature. This effect significantly alters the device transient characteristics (Moore, 1980) with respect to ideal behavior and makes the measured OCVD characteristics strongly temperature dependent, especially below room temperature under monochromatic illumination level (Castanier et al., 1981).

In this study, the theoretical method suggests that minority carrier lifetime is not directly accessible parameter. It can be measured as an effective minority carrier lifetime, which is strongly temperature depended. According to our model, effective minority carrier lifetime decreases exponentially with temperature. This behavior cannot be explained by ordinary OCVD theory (Lederhandler and Giacoletto, 1955). This denotes that our proposed analyzing method is valid otherwise; the expected OCVD curve is going to be consisting of stretch exponential form (see Eq. (1)).

The OCVD characteristic can be significantly influenced by the capacitive effect, which can be considered as consisting of both depletion layer capacitance (C_d) and diffusion capacitance (C_{diff}) under sufficient monochromatic illumination level. The diffusion capacitance of the injected carriers dominates over the depletion layer capacitance (Schroder, 1990; Sinton and Swanson, 1987). The OCVD time introduced by a junction capacitance causes that the minority carrier lifetime can be overestimated (Green, 1983). It is necessary that the minority carrier lifetime is much larger than the time constant for diffusion to calculate an effective minority carrier lifetime from the OCVD (Schroder, 1990; Sinton and Swanson, 1987). In addition, there may arise some uncertainty in minority carrier lifetime due to fact that our porous Si solar cell-type is "back surface field" (BSF) solar cell (Sze, 1981) generally contains two interfaces (p^+/p and p/n^+ contact intercept region) in the junction formation, forasmuch as OCVD method measures the recombination lifetime. At that point, a reconstruction technique/model is required to extract the effective minority carrier lifetime from the measured non-traditional OCVD data in the presence of an interface effect.

OCVD technique was one of the earliest methods for minority carrier lifetime determination. However, very little attention has been paid to the temperature depended OCVD at monochromatic illumination of solar cells in the literature, especially at low temperature. In this study, effective minority carrier lifetime has been calculated from the temperature dependent OCVD measurements by using an alternative extraction technique.

2. Theory

The time variation of OCVD ($\Delta V_{oc}(t)$) is given elsewhere (Lederhandler and Giacoletto, 1955),

$$\Delta V_{oc}(t) = \frac{k_B T}{q} In\left[1 + e^{\frac{-t}{\tau_e}}\left(e^{\frac{qV_i}{k_B T}}\right)\right] \quad (1)$$

where t is the time (for collecting data during the transient response), V_i the junction voltage at $t = 0$, τ_e the effective minority carrier lifetime, T temperature and q, k_B are the well known constants.

Let $z = e^{\left(\frac{qV_i}{k_B T} - \frac{t}{\tau_e}\right)}$. For $t \rangle\rangle \left(\frac{qV_i}{k_B T}\tau_e\right)$, z value approximates to zero. However, if this condition can be met, it can be shown using the approximation $In(1 + z) \approx z$,

$$\Delta V_{oc}(t) = \frac{k_B T}{q}\left(e^{\frac{qV_i}{k_B T}}\right)e^{\frac{-t}{\tau_e}} \quad (2)$$

where $\Delta V_{oc}(t) = V_{oc}(t) - V_{bias}$. V_{bias} is the final value of the open circuit voltage which depends on the intensity of the bias light. The voltage decay is constituted of a sum of exponentially decaying modes (Joardar and Schroder, 1992). It is obvious from Eq. (2) that the OCVD curve is represented by single exponential function. The voltage decay curve can be approximated as a pure exponential. That is;

$$\Delta V_{oc}(t) = \Delta V_{oc}(0)e^{\frac{-t}{\tau_e}} \quad (3)$$

Several equivalent circuits have been proposed for determining solar cell ac parameters using different electrical characterization technique (Deshmukh and Nagaraju, 2005; Deshmukh et al., 2004; Kumar et al., 2000; Suresh, 1996; Sharma et al., 1992). Especially, the study (Deshmukh et al., 2004) is of great practical interests. In this paper, we propose an alternative technique for this measurement and show how the equivalent circuit can be further improved. Equivalent circuit model, useful in a transient analysis, should include the diffusion capacitance, dynamic resistance R_d, series resistance R_s and interface elements (R_{int}) and (C_{int}).

Under low frequency (high excitation period) excitation condition the diode capacitance arises from two distinct regions of charges (Jasprit, 1995).

(i) Under reverse biased conditions, there are fundamentally no injected carriers to the depletion region and the junction capacitance dominates. A dipole of fixed positive and negative charge in the depletion region of the junction constitutes the junction capacitance.

(ii) Under forward bias condition, there are minority carrier injections to the depletion region. The diffusion capacitance arises from minority carrier injection from the region outside the depletion region.

For the analysis of the OCVD characteristic of simulated solar cell, equivalent electrical circuit has been proposed corresponding to solar cell structure. For the OCVD measurement, one should use a light source,