Thin Solid Films 546 (2013) 353–357

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Scanning probe study on the photovoltaic characteristics of a Si solar cell by using Kelvin force microscopy and photoconductive atomic force microscopy

Jinhee Heo, Soonho Won *

Advanced Characterization and Analysis Department, Korea Institute of Materials Science (KIMS), Changwon 641-831, Korea

ARTICLE INFO

Available online 1 May 2013

Keywords:
Photovoltaic
Surface potential
Photoinduced current
Solar cell
Scanning probe microscopy (SPM)

ABSTRACT

Poly-Si-based solar cells, prepared via conventional Si processes including phosphoryl chloride($POCl_3$) doping and diffusion, were investigated in this study in terms of their electrical and optical properties, including open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor, external quantum efficiency and efficiency, employing a few recognized test methods. Also, we compared the experiment results from an identical specimen via Kelvin force microscopy (KFM) and photoconductive atomic force microscopy (PC-AFM), respectively, verifying that the scanning probe technique is very effective both in photovoltaic effect measurement and mechanism establishment. When the results of both conventional and nano-probing techniques are compared, the behavior of the surface potential property is similar to the V_{oc}, and that of the photoinduced current property is similar to the I_{sc}. Through this study, we have demonstrated that the KFM and the PC-AFM are effective tools to monitor and evaluate the properties of solar energy–producing materials and devices.

1. Introduction

With global investment in and research and development of eco-friendly energy on track, photovoltaic devices rapidly reach the European and Chinese markets. Technologies have advanced also in conventional, crystalline silicon-based solar cells to improve efficiency and reduce costs. Higher efficiency in solar cells requires optimized manufacturing and having the photovoltaic effect mechanism expressly verified, which may lead to more precise photovoltaic material design and subsequently to more effective solar cell structure, all of which may eventually secure spinal technologies to acquire remarkable a photovoltaic efficiency.

Fourier transforms, infrared spectroscopy and Raman spectroscopy as well as the nano-probe technique are currently used to evaluate photovoltaic effect on the nanometer scale. Especially, conductive atomic force microscopy (C-AFM) serves as a tool for electrical property analysis of nano-materials, while a variant has been recently developed to measure the photoinduced current, brought about by the light irradiation, in solar cells. Scanning probe microscopy (SPM) makes the best use of the nano-probe in the analysis of topography and electrical, magnetic and mechanical properties of the specimen [1–6].

This study employed Kelvin force microscopy (KFM) and photoconductive AFM (PC-AFM) to evaluate the photovoltaic effect of poly-Si-based solar cells. By employing a KFM system, we can observe changes of surface potential, which originated from the collected photo-induced carriers on the device surface by the photovoltaic effect. Since the amount of collected carriers and value of surface potentials are correlated with an intensity of irradiated light, we were able to evaluate a V_{oc} property of photovoltaic device indirectly through a KFM measurement. The PC-AFM system, developed on the basis of the conductive-AFM technology, evaluates on the nanometer scale the separation, transport and collection of the charges generated on solar cells [7–9].

Poly-Si-based solar cells, prepared via conventional Si processes including phosphoryl chloride($POCl_3$) doping and diffusion, were investigated in this study in terms of their electrical and optical properties, including open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor, external quantum efficiency (EQE) and efficiency, employing a few recognized test methods. The authors compared the results of the experiment from an identical specimen via KFM and PC-AFM, respectively, verifying that the scanning probe technique is very effective both in photovoltaic effect measurement and mechanism establishment.

2. Experiments

We investigated the photovoltaic effects of light irradiation on solar cells by using the KFM and PC-AFM. Initially, we prepared *p*–*n* junction-structured poly-Si wafer–based solar cell devices. A 200-μm-thick poly-Si wafer was heated in a diffusion furnace at temperatures up to 850 °C with $POCl_3$, forming a *p*–*n* junction on the surface of the wafer by means of diffusion. The thickness of the diffused

* Corresponding author. Fax: +82 55 280 3626.
E-mail address: wsh@kims.re.kr (S. Won).

http://dx.doi.org/10.1016/j.tsf.2013.04.076

Table 1
Electrical properties of poly-Si solar cell devices.

V_m (V)	I_m (mA)	V_{oc} (V)	I_{sc} (mA)	P_{max} (mW)	FF	J_{sc} (mA/cm^2)	Efficiency (%)
0.49	41.3	0.59	48.5	20.0	0.7	32.9	13.6

n-type region was about 300 nm, and its sheet resistance was about 60 Ω/□.

The dimension of the fabricated solar cell was 1 cm × 1.5 cm. The thickness of the antireflection layer (SiN_x) that was deposited by plasma-enhanced chemical vapor deposition process was 76 nm, and its refractive index was 1.97. After the SiN_x layer was deposited, the bottom electrodes and top electrodes were fabricated by screen printing with silver paste. The thicknesses of the bottom electrodes and the top electrodes were 60 μm and 20 μm, respectively. To form the ohmic contact for the electrodes, the solar cell devices were annealed in 680 °C with rapid thermal processing (RTP). The electrical properties of the prepared solar cells were measured by using the K201 solar cell simulator system (McScience Inc., Korea). The results of the measurement, as summarized in Table 1, were that the V_{oc} was 0.59 V and the I_{sc} was 48.5 mA. Also, the values of fill factor and efficiency of the devices were 0.7 and approximately 13.6%, respectively. In addition, the EQE, which is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy source shining on the solar cell from outside, was analyzed, and the results are shown in Fig. 2.

Light source intensity varied from 0 to 130 mW/ at intervals of 10 mW/ to investigate V_{oc} and I_{sc} properties according to irradiation intensity onto the device and compare them to the results via SPM evaluation. Fig. 3 shows the consequential current–voltage (*I–V*) curve of solar cells. After the characterization of the operating properties of solar cells, we used the E-sweep SPM model (Seiko Instruments, Japan) along with an external light source of controllable intensity to induce a photovoltaic phenomenon (Fig. 1). A Pt-coated Si cantilever tip with a spring constant of 3 N/m was used to measure the surface potential and the photoinduced current, by using the KFM and PC-AFM system. Before the scanning probe analysis, the natural oxide layer on the sample surface was removed by being rinsed with a buffered HF solution.

For improvement of the contact resistance between the Pt-coated cantilever tip and the *n*-type Si surface, a thin Au (~8 nm) film was coated on the sample surface by using a DC sputtering system with a patterned shadow mask. As a result, the contact resistance was remarkably decreased in the Au-coated area, and the thin metal coating on the sample surface proved very effective as well as being necessary for PC-AFM measurement [11].

The surface potential of the specimens was measured by KFM, in which conductive cantilever tips were employed with their surface coated with Pt and its resonance frequency was 27 kHz. The surface potential images have been attained under AC bias oscillating from −2.5 V to +2.5 V with frequency of 25 kHz for surface potential sensing. An area of 100 × 100 μm was scanned without a DC bias applied, in which the irradiation varied from 0 to 15 μW/ at intervals of 2.5 or 5 μW/. After a spot was selected for scanning, a 100-μm × 100-μm scan was carried out with 0 V bias under conditions of various light intensities in order to get a detailed characterization of the correlation between the light intensity and the photoinduced current. During this process, the light intensity of the halogen lamp was varied from 0 to 15 μW/, and the topography images and current images were simultaneously obtained. From the quantitative analysis of the electrical properties of the photovoltaic effect, which were measured using the PC-AFM, we calculated a maximum current level under each light condition.

3. Results

The *p–n* junction-structured poly-Si-wafer-based solar cell devices were fabricated by using a $POCl_3$ diffusion process. The electrical properties of the prepared solar cell devices were measured, and the results are shown in Table 1. The V_{oc} is 0.59 V, and the I_{sc} is

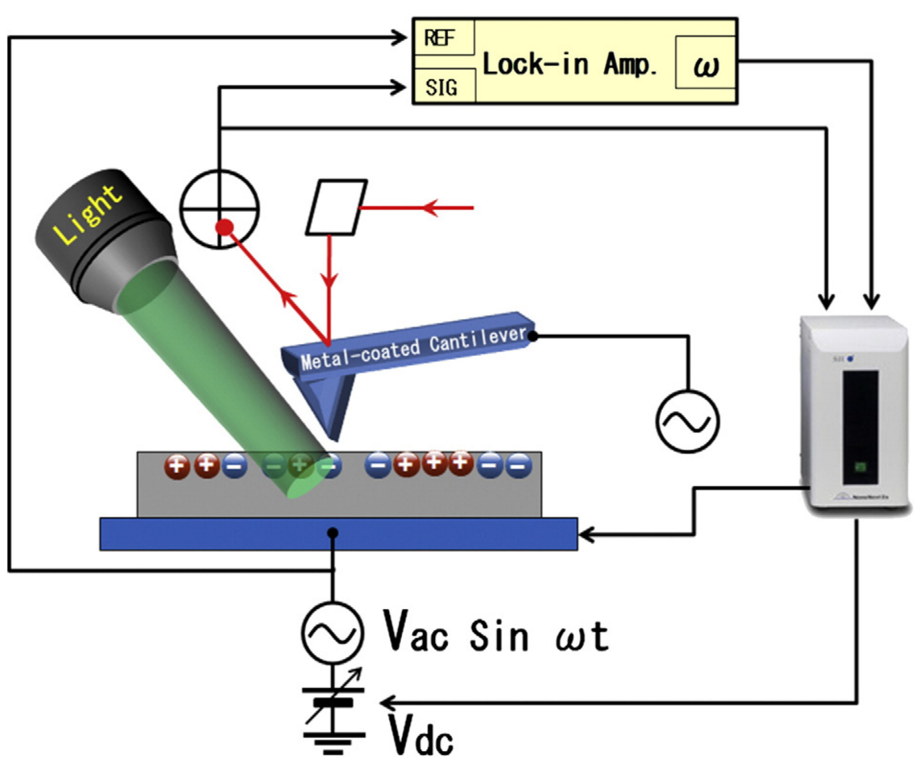

Fig. 1. Schematic of the Kelvin force microscopy (KFM) system. A Pt-coated tip was used as an electrode, and so the intensity of light could be controlled [10].