Journal of Energy Technologies and Policy www.iiste.org
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.3, No.11, 2013 – Special Issue for International Conference on Energy, Environment and Sustainable Economy (EESE 2013)

Temperature Dependent Current-voltage Characteristics of P-type Crystalline Silicon Solar Cells Fabricated Using Screen-printing Process

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Abstract

We have fabricated p-type crystalline silicon (Si) solar cells using screen-printing process and investigated their electrical properties. Ph screen printing process led to the uniform formation of n+ emitter. As a result of interaction between Ph-dopant paste and Si substrate, a phosphosilicate glass layer was formed on n+ emitter surface. The current-voltage characteristics were carried out in the temperature range of 175 – 450 K in steps of 25 K. The variation in current level at a particular voltage strongly depended on temperature, indicating that the current transport across the junction was a temperature activated process. The reverse leakage current gradually increased with increasing measurement temperature up to 350 K, above which it rapidly increased. Arrhenius plot of the leakage current revealed that reverse leakage current in low and high temperature regions were dominated by the tunneling mechanism, and generation and recombination mechanism, respectively.

Keywords: P-type Si solar cell, screen-printing, I-V, tunneling, generation and recombination, reverse leakage current

1. Introduction

Crystalline silicon (Si) solar cells constitute of above 85% of the world photovoltaic (PV) market with a tendency to increase their market share due to the combination of comparatively higher conversion efficiency, long-term stability and optimized manufacturing techniques (Green et al., 2012). The development of fast and cost-effective processing technologies for high efficient crystalline Si solar cells plays a key role in the large-scale penetration of PV in the total energy system. Analysis of the current-voltage (I-V) characteristics of crystalline Si solar cells obtained only at room temperature does not give detailed information about the current transport through emitter. In fact, I-V analysis at room temperature neglects many possible effects that cause the high leakage current. The temperature dependence of I-V characteristics gives a better understanding of the leakage mechanism involved in crystalline Si solar cells. Previously, many researchers reported on the physical properties of screen-printed Ag contacts on an n+ emitter surface in crystalline Si solar cells. For instance, Ballif et al. (Ballif et al., 2003) investigated the structural and electronic properties of Ag thick film contacts screen printed on P-diffused Si wafers. Li et al. (Li et al., 2009) demonstrated the microstructural properties of the Ag/emitter contact of crystalline Si solar cells fired at temperatures from below to above optimal conditions by means of electron microscopy, and reported the evolution of interfacial microstructure from one richly decorated nanometer-size Ag colloids into one with many Ag crystallites grown onto the emitter surface. They suggested that the tunneling mechanism is responsible for the current extraction in these cells. Jeong et al. (Jeong et al. 2010) investigated the microstructural and chemical properties of screen-printed Ag contacts on an n+ emitter surface in crystalline Si solar cells. In the present work, we have investigated the reverse current leakage mechanism of p-type crystalline Si solar cells fabricated using screen printing process using I-V characteristics measured at the temperature range of 175 K – 450 K in steps of 25 K.

2. Experimental Details

Figure 1 shows the schematic diagram and key process flow of screen-printed p-type crystalline Si solar cell used in this work. Czochralski (CZ) (100) boron doped p-type monocrystalline Si wafers having a resistivityof 2 – 5 Ω·cm, a thickness of about 220 mm and size of 4.0 cm × 4.0 cm were used as a starting material. After removing the native oxide using a buffered oxide etchant (BOE), saw damage on the surface was etched using a KOH solution. The wafer was then rinsed with deionized water. Surface texturing was carried out using a mixture of KOH and isopropyl alcohol. Phosphorus (Ph) screen printing was used to form an n+ emitter region in the textured Si surface followed by furnace annealing at 840°C for 20 min under flowing O_2 ambient. The wafers were then dipped in BOE to remove phosphosilicate glass layers formed as a result of the reaction between phosphorous paste and Si. The sheet resistance of the screen printed n+ emitters was measured to be 64 Ω/square. The 80 nm thick SiN_x film was used as an antireflection layer deposited on the surface using plasma enhanced chemical vapor deposition (PECVD). Next, an Al paste was screen-printed on the backside and dried at 200 C. The Ag grid was then screen-printed on top of the SiN_x film and Ag and Al contacts were co-fired (single firing step) in a lamp-heated belt furnace. During co-firing process, Ag Ohmic contact to n+ emitter and Al back surface field (BSF) were formed. The efficiency of the manufactured p-type crystalline Si solar, measured using solar simulator at the condition of AM 1.5 Global with flash illumination, was found to be 16.6 %. Open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), and fill factor (FF) were summarized in table 1. Microstructure of Ph screen-printed n+ emitter was characterized transmission electron microscopy (TEM) equipped with energy dispersive X-ray spectroscopy (EDX). The I-V measurements were carried out using precision semiconductor parameter analyzer (Agilent 4156C) in the temperature range of 175 K – 450 K in steps of 25 K.

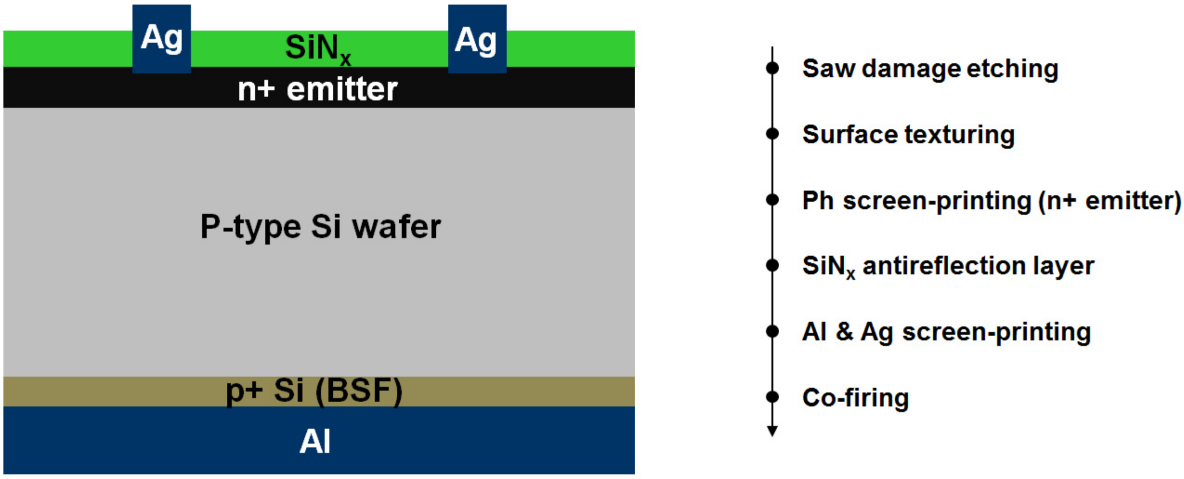

Figure 1. Schematic diagram and key process flow of screen-printed p-type crystalline Si solar cell used in this work.

Table 1. Summary of V_{oc}, J_{sc}, FF, and efficiency of p-type crystalline Si solar cell manufacture using screen printing process

V_{oc}	J_{sc}	FF	Efficiency
568.1 mV	39.0 mA/cm^2	74.97 %	16.6 %

3. Results and Discussion

Figure 2 represents cross-sectional bright field TEM image obtained from the Ph screen printed n+ emitter. In order to reveal the Ph distribution, TEM specimen was chemically etched using using a mixture of $HF:HNO_3$: CH_3COOH (1:100:25) for 5 s. The image clearly showed dark thickness fringes formed as a result of the concentration-dependent etch in the Ph doped region. Such fringes can be converted into isoconcentration contours since they consist of the same concentration points. The relatively even isoconcentration contours indicated that Ph screen printing process led to the homogenous Ph diffusion to Si substrate, resulting in the uniform formation of n+ emitter. The chemically delineated junction depth, defined as the distance from emitter surface to the last visible isoconcentration contour was found to be ~ 70 nm. In particular, a layer with a thickness of ~ 20 nm was clealy visible on the n+ emitter as indicated by an arrow. For the identification of such a layer, EDX line profiling was carried out using a scanning electron probe with a size of 1 nm over the sample (Fig. 3). The STEM-EDX line profiling exhibited that this layer consisted of O, Si, and P atoms. This suggests that during the Ph screen printed emitter process, interaction between Ph-dopant paste and Si substrate caused by thermal treatment resulted in the formation of a phosphosilicate glass (PSG) layer on Si surface.

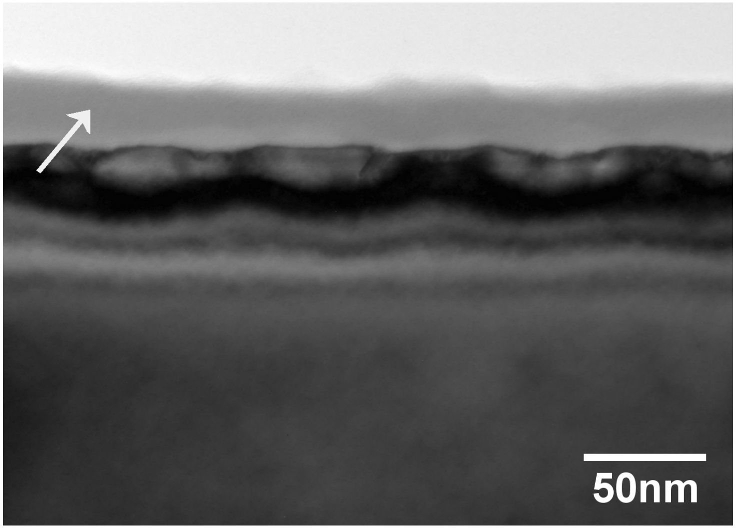

Figure 2. Cross-sectional bright field TEM image obtained from the Ph screen printed n+ emitter.

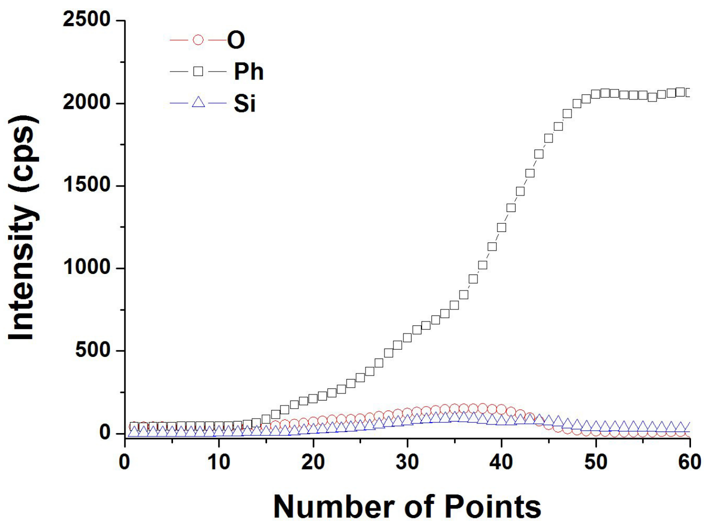

Figure 3. EDX line profile for O, Ph, and Si atoms taken from Ph screen printed n+ emitter

Figure 4(a) shows the I-V characteristics of p-type crystalline Si solar fabricated using screen printing process measured at the temperatures ranging from 175 to 450 K. Regarless of measurement temperature, rectification behavior was clearly visible, which is typical feature of n+/p junction. In particular, at low temperatures, the variation of reverse leakage current at a particular voltage (2 V) with temperature was very low while a relatively large current variation was observed at high temperatures, as shown in Fig. 4(b). Such a variation of reverse leakage current depending on measurement temperature could be associated with the current transport across the n+/p junction governed by a temperature activated process. Namely, only few electrons are able to flow across of the junction at low temperatures. However, at higher temperatures, more and more electrons have sufficient energy to flow across the junction.

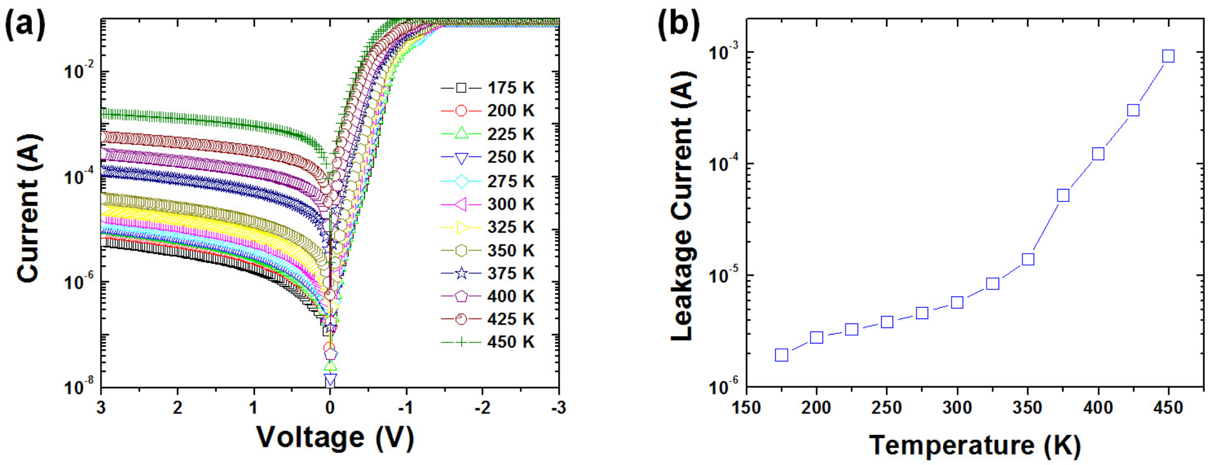

Figure 4. (a) I-V characteristics of p-type crystalline Si solar fabricated using screen printing process measured at the temperatures ranging from 175 to 450 K, and (b) plot of reverse leakage current measured at 2 V versus temperature.

In order to investigate the leakage mechanism, Arrhenius plot of the leakage current of the manufactured cell was used, as shown in Fig. 5. The reverse leakage current was measured at 2 V in the temperature range 175 K – 450 K. The temperature dependence of the reverse leakage current as revealed by the slope of the Arrhenius plot provides useful insight into the mechanism for reverse leakage current (Lee et al., 1998). The activation energy (E_A) of reverse leakage current is close to the band gap of silicon (E_g) when dominated by diffusion and close to half the band gap ($E_g/2$) when dominated by generation and recombination. From the linear fit to slope of Arrhenius plot, E_A of 0.50 eV was obtained in the high temperature region which is close to half of the band gap (E_g). This suggests the possibility of the leakage current to be dominated by generation and recombination mechanism. Further, almost zero activation energy was obatained at the low temperature region, implying that the reverse leakage current is independent of the measurement temperature. Hence, the current in the low temperature region is dominated by the tunneling mechanism.

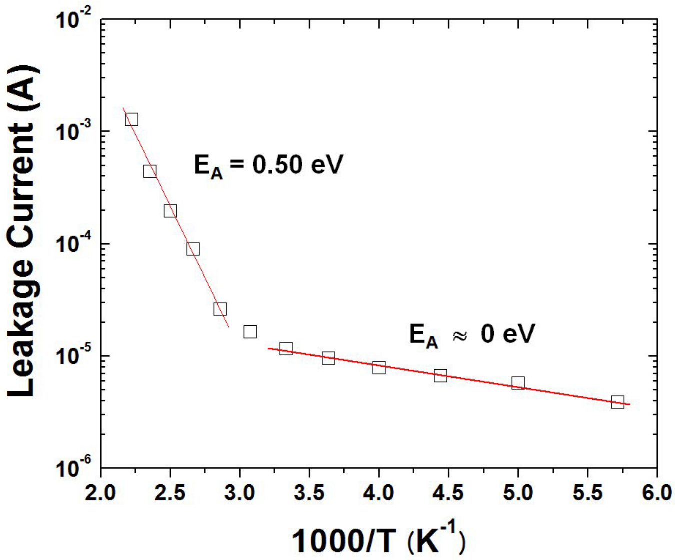

Figure 5. Arrhenius plot of the leakage current of p-type crystalline Si solar fabricated using screen printing process.

4. Conclusion

We have investigated the reverse leakage current mechanism of screen-printed p-type crystalline Si solar cells with an efficiency of 16.6 %. During the Ph screen printing process, relatively uniform n+ emitter was formed with the PSG layer formed as a result of interaction between Ph-dopant paste and Si substrate. The I-V measurements showed that carrier conduction across n+ emitter was a temperature activated process. An increase in measurement temperature resulted in the increase in reverse leakage current. From the linear fit to slope of Arrhenius plot, generation and recombination mechanism could be a main cause of carrier conduction in reverse bias at high temperature while reverse leakage current was dominated by the tunneling mechanism at low temperature.

Acknowledgements

This work was supported by “Human Resource Development Program (201040100660)” of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant and Honam Leading Industry Office through the Leading Industry Development for Economic Region (R0001244) funded by the Ministry of Knowledge Economy, Korea.

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