Local photovoltaic characterization for silicon thin film solar cells using a scanning probe microscope

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Abstract. The photovoltaic characterization of silicon thin film solar cells with nano-scale spatial resolution is demonstrated by a new characterization method developed using a scanning microscope. In the surface topography of p-i-n type amorphous silicon thin film solar cells, large and small convex grains corresponding to the textured surface of an Asahi U-type substrate and the crystalline grains in the n-type microcrystalline silicon layer are found. In the local photo-current image, distribution in local photo-current correlated with the structure of the n-type microcrystalline silicon layer is observed in the p-i-n type amorphous silicon (a-Si:H) thin film solar cells. The local surface potential in amorphous silicon thin film solar cells with light irradiation is also evaluated. In the local surface potential image of the p-i-n a-Si:H thin film solar cells without light irradiation, the local surface potential on the large convex grains found in the surface topography is smaller than that in the concave region between the large convex grains. Similar distribution of the local surface potential is observed in the local surface potential images with light irradiation. The local surface potential difference between the large convex grains and the concave region decreases with increasing power of the irradiation light.

1. Introduction

Microcrystalline materials such as hydrogenated microcrystalline silicon (µc-Si:H) are used as a photo-absorption layer and doped layer materials in Si thin film solar cells such as µc-Si:H and amorphous Si (a-Si:H) thin film solar cells. The microcrystalline materials have a hetero-structure composed of an amorphous phase, nano-sized crystalline grains, and grain boundaries. Therefore, local properties in the nano-scale range are different. Typical Si thin film solar cells are deposited on glass substrates coated with textured transparent conductive oxide (TCO). The properties of a-Si:H and µc-Si:H films are affected by the preparation on the textured TCO [1, 2]. Based on these points, the local photovoltaic performance of Si thin film solar cells in the nano-scale range would be different. Consequently, the obtained efficiency is the combination of the local photovoltaic performances. In order to improve the photovoltaic performance of silicon thin film solar cells, understanding the local properties is important. However, the photovoltaic performance for the Si thin film solar cells has been mostly evaluated by macroscopic measurements.

Light-beam-induced current (LBIC) is used in the measurement of local characterization in the polycrystalline silicon solar cells [3]. Compared with the EBIC, higher spatial resolution is necessary.
in the local characterization of Si thin film solar cells because microcrystalline materials with nano-scale structure are used as photo-absorption and doped layer materials in the Si thin film solar cells. An atomic force microscope (AFM) is a scanning probe microscope (SPM) which is an imaging technique at nano-scale spatial resolution. Using the method based on the AFM technique, local electrical measurement with nano-scale spatial resolution was conducted [4-6]. However, local electrical characterization in only single films was carried without light irradiation. Therefore, we have developed a local photovoltaic characterization method using the AFM technique.

In this report, the newly developed local photovoltaic characterization method is explained. Using the developed method, the first measurement of the local surface potential in Si thin film solar cells with light irradiation was conducted in this work.

2. Development of local photovoltaic characterization method
At first, a local photo-current measurement system was developed using the scanning near-field microscope (SNOM) technique [7]. In p-i-n type Si thin film solar cells, light is irradiated from the p-layer side. Using the system based on the SNOM technique, the light is irradiated from the n-layer side in the p-i-n type solar cells and the result is not obtained in actual behaviour. Therefore, we developed a new local photo-current measurement system in which light could be irradiated from the p-layer side [8].

![Figure 1. Schematic illustration of a local photo-current measurement system based on conductive-AFM.](image)

Figure 1 shows the schematic illustration of the local photo-current measurement system. This system is based on conductive-AFM (Seiko Instruments Nano-Technology, SPI3800N-SPA400). In order to measure the local current under light irradiation from the p-layer side of p-i-n type solar cells, a new attachment of a sample holder with a light source was developed. A halogen lamp (white light) and LED light (wavelength of 625 nm or white light) were used as light sources. Spot size of the light at the surface of solar cells is less than 2 mm in diameter. The scanning frequency is typically 0.5 Hz. The conductive cantilever and sample holder were connected to a pico-ampere current meter and an electrical source of a sink current type which were embedded systems in the AFM. In this measurement, the electrical contact property between the cantilever and solar cell is important. In the early stage, Rh coated Si cantilevers (Seiko Instruments, SI-DF3-R) with a spring constant of 1.6 N/m were used as a probe. However, the contact property between the Rh coated cantilever and solar cell was not good, since a shottky barrier would form between the cantilever and the solar cell. The electrical contact property between the conductive cantilever and solar cells was improved by coating with a defective ZnO thin film deposited by DC-sputtering at room temperature [8]. Using this system, local photo-current - voltage characteristics and photo-current mappings can be measured. However, the local oxidation led to the formation of a SiO₂ thin film on the surface of Si thin film solar cells, because this measurement was conducted at room temperature in air [9]. We proposed topographical and Current-Voltage Imaging (TCVI) as a technique to avoid local oxidation [9, 10]. Using the TCVI,
the topography and local photo-current – voltage characteristic can be obtained simultaneously in only a single scan. Therefore, the local photo-current – voltage characteristics and local photo-current images can be obtained without local oxidation.

An example of the results measured using the developed system is shown. Figure 2 shows (a) the surface topography and (b) photo-current image in the p-i-n type a-Si:H thin film solar cell. Here, the structure of the a-Si:H thin film solar cell was an Asahi U-type substrate (textured SnO$_2$ on glass)/p-type a-Si$_{1-x}$C$_x$:H (15 nm)/i-type a-Si:H (450 nm)/n-type μc-Si:H (47 nm) and the conversion efficiency obtained by macroscopic measurement was 7.1%. LED light with a wavelength of 625 nm was used as the irradiation light and the photon energy of the irradiation light was larger than the band gap energy of i-type a-Si:H used as a photo-absorption layer material. As the local photo-current image was measured, a bias voltage of -2 V was applied to the sample holder connected to TCO using a silver paste. The brighter regions in the surface topography and photo-current image indicate higher surface height and larger current flow, respectively. In the surface topography, large and small convex grains were found. In the surface topography of the Asahi U-type substrate, large convex grains were found [10]. In the surface topography of the n-type μc-Si:H film deposited on the glass substrate, small convex grains were found [11]. The size of the large convex grains found in the surface topography of the Asahi U-type substrate and that of the n-type μc-Si:H film deposited on the glass substrate was almost the same as that of the p-i-n type a-Si:H thin film solar cell, respectively. Therefore, the large and small convex grains correspond to the textured surface of the Asahi U-type substrate and crystalline Si grains, respectively. Comparing the two images, the photo-current on the crystalline Si grains was larger than that in the grain boundaries, and the photo-current was very small in the region between the large convex grains. This result suggests that photo-current flows mainly through the crystalline Si grains in the n-type μc-Si:H layer.

Based on this result, the local photo-current image with nano-scale resolution can be measured in Si thin film solar cells using this system.

![Figure 2](image_url)

**Figure 2.** (a) Surface topography and (b) local photo-current image of the a-Si:H thin film solar cell.

### 3. Local surface potential in a-Si:H thin film solar cells with light irradiation

In the developed system, local surface potential images with light irradiation were also measured using a kelvin force microscope (KFM) unit instead of a conductive-AFM unit. In this measurement, the surface topography and photovoltaic properties can be obtained simultaneously in a single scan. Using this system, we measured the local surface potential in a-Si:H thin film solar cells. Au coated Si cantilevers (Seiko Instruments, SI-DF3-A) with a spring constant of 1.6 N/m was used as a probe and the scanning frequency was 0.4 Hz. The structure of the a-Si:H thin film solar cell used in this work was the Asahi U-type substrate/p-type a-Si$_{1-x}$C$_x$:H (15nm)/i-type a-Si:H (450nm)/n-type μc-Si:H (45nm) and the conversion efficiency obtained by macroscopic measurement was 6.4%.
Figure 3 shows (a) the surface topography and (b) the local surface potential image of the a-Si:H thin film solar cell without light irradiation. The brighter regions in the surface topography and the local surface potential images indicate higher surface height and larger surface potential, respectively. In the surface topography, an uneven surface was observed. This large convex grain is related to the textured surface of the Asahi U-type substrate as explained above. Comparing the two images, the surface potential on the large grains was smaller than that in the region between the large convex grains. In n-type μc-Si:H films deposited on Asahi U-type substrates, similar tendency is obtained [11]. Therefore, this surface potential distribution observed in the a-Si:H thin film solar cell would be related to that in the n-type μc-Si:H layer. On the growth of the μc-Si:H film on the Asahi U-type substrate, the collision of crystalline columns occurs, resulting in the formation of grain boundaries [1]. In the local surface potential image of the n-type μc-Si:H film on the glass substrate, the local surface potential on the small convex grains found in the surface topography was smaller than that in the region between the small convex grains, i.e., grain boundary. Therefore, the surface potential distribution observed in the surface potential images of the n-type μc-Si:H films deposited on the Asahi U-type films would be related to the grain boundary [11].

Next, we measured the local surface potential images with light irradiation. Here, the white light LED (OSRAM, LCW G6Sp-CBEB-409Q) was used as the irradiation light and the power of the irradiation light was varied from 0 to 2.24 mW/cm². Figure 4 shows (a) the surface topography and (b) the local surface potential image of the a-Si:H thin film solar cell with light irradiation. Here, the power of the irradiation was 2.24 mW/cm². Comparing Figures 3 and 4, almost the same surface potential distribution was observed with/without light irradiation. However, the numerical value was changed by light irradiation. Variation in the average of the local surface potential in the scanning area corresponds to that of the macroscopic surface potential by light irradiation. In order to understand the change of the surface potential by light irradiation, the average of the local surface potential was first obtained.

Figure 5 shows the dependence of the average of the local surface potential on the power of the irradiation light. In Figure 5, the average of surface potential decreased with increasing power of the irradiation light. This result could be understood as follows. In a-Si:H thin film solar cells, photo-generated electrons are collected into the n-layer. In this measurement, the potential on the p-layer is connected to the conductive cantilever. Therefore, the potential on the n-layer decreases by light irradiation. As a result, the average of local surface potential decreases with increasing power of the irradiation light. In Figures 3 and 4, the potential difference was found between the large convex grain and concave region, i.e., grain boundary. The potential difference $\Delta \phi_{ave}$ between the large convex grain and grain boundary was estimated as:
Here, $\phi_{CGave}$ and $\phi_{GBave}$ were averages of the potential on the top of the large convex grains and at the bottom of the concave region between the large convex grains, i.e., grain boundary, respectively. Figure 6 shows the dependence of the potential difference $\Delta \phi_{ave}$ between the large convex grain and grain boundary on the power of the irradiation light. In Figure 6, the potential difference $\Delta \phi_{ave}$ decreased with increasing power of irradiation. One possible cause is the potential difference in the n-layer. In the n-type $\mu$c-Si:H films deposited on the Asahi U-type substrates, the local potential on the large convex grain is smaller than that in the grain boundary. Therefore, electrons collected into the n-layer would move from the large grains to the grain boundary. Thus, potential in the grain boundary decreases more than that on the large convex grain. As a result, the potential difference decreases with increasing power of irradiation. These results suggested that the grain boundaries in the n-type $\mu$c-Si:H layer might be one of the factors which causes decreasing efficiency in a-Si:H thin film solar cells. At present, however, the relation between the efficiency and the change of the $\Delta \phi_{ave}$ is not clear. Therefore, further investigation using a-Si:H thin film solar cells with different efficiencies is necessary.

Figure 4. (a) Surface topography and (b) local surface potential image of the a-Si:H thin film solar cell with light irradiation. The power of irradiation was 2.24 mW/cm$^2$.

Figure 5. Dependence of the average of the local surface potential on the power of irradiation.
4. Summary
We developed a new local photovoltaic characterization method for Si thin film solar cells based on AFM and demonstrated local photovoltaic characterization with nano-scale spatial resolution using this method. Local photo-current and local surface potential images were observed in a-Si:H thin film solar cells. These results suggested that the local photovoltaic performance with nano-scale spatial resolution can be evaluated using this method. Based on these results, this method is useful for the evaluation of not only Si thin film solar cells, but also multi-crystalline solar cells such as CuInGaSe solar cells.

![Image](image_url)

**Figure 6.** Dependence of the potential difference $\Delta \phi_{ave}$ between the large convex grain and grain boundary on the power of the irradiation light.

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