Morphology and Conductivity Characteristics of Polycrystalline Silicon Thin Film Deposited by Plasma-Enhanced Vapor Deposition in Textured Substrate

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Abstract. We investigate the characteristics of polycrystalline Silicon (poly-Si) thin films for solar cells produced by very high frequency (VHF) plasma enhanced chemical vapor deposition using a conductive scanning probe microscope (SPM). We measure the surface morphology and local current images are simultaneously of the poly-Si layers with a thickness, \(d=2\ \mu\text{m}\), formed on textured Ag/SnO\(_2\)/glass in the range of RMS based-textured substrate (a) \(\sigma=85\text{nm}\), (b) \(\sigma=42\text{nm}\) and (c) \(\sigma=2\text{nm}\) respectively. Influences of the substrate texture on the crystal growth as well as the local current flow are discussed. Where we found that the average of local current proportional with crystallinity, where the poly-Si layer that has rich crystallinity indicated low conductivity that yield high local current.

Introduction

One of the breakthroughs in producing inexpensive and stable photovoltaic materials is the low temperature growing polycrystalline silicon (poly-Si) thin film produced by VHF plasma-enhancing chemical vapor deposition (PECVD). In several reports it was stated that poly-Si thin films prepared using PECVD fabrication showed variations in microstructural properties from mixed-crystal-amorphous states to crystalline states that reached 100\% with different crystallographic orientations. [1-5].

In addition, the microstructure of poly-Si is very heterogeneous, so it is necessary to investigate the electrical properties monoscopically. The method used is to measure local conductivity using a scanning probe microscope (SPM), where the SPM method can measure electrical quantities in nanoscale. [6, 8, 9, 11-15].

In this work, surface morphology and local current images evaluated by a conductive scanning probe microscope (SPM) technique are shown for the photovoltaic poly-Si thin films deposited by VHF-PECVD, and also, we performed the microscopic analysis of poly-Si microstructure by microstructure of crystalline volume fraction, \(X_c\).

Material and Method

We prepared the sample with structure was glass / Ag / poly-Si / ZnO:Al. Sputtering technique has been utilize to coat the 10-nm-thick ZnO:Al transparent electrodes and the 100-nm thick Ag layer. The undoped poly-Si layers for all samples are identical with those of i-layer in 9\% efficiency p-i-n solar cells [7,10]. The thicknesses of poly-Si were 2 \(\mu\text{m}\).
A SPM system (Park Scientific Instrument CP-R) is utilized to evaluate the topological and local current images. A schematic diagram of conductive SPM used in this study is shown in Fig. 1. A conductive cantilever made of highly doped silicon coated with Pt was used for observing the surface topography in the contact atomic force microscope (AFM) mode and the local current image simultaneously. The SPM measurements were performed in ex-situ, so that, to minimize influences of the surface oxidation after the deposition of the poly-Si layer, the sample was kept in vacuum, and the coated by ZnO:Al for observing the current image, and then measured as soon as possible. After the second time scanning, the local current tends to markedly decrease. The dc current was obtained by applying a bias voltage of 1 V onto the ZnO:Al electrode when the counter Ag electrode was set as ground. The crystalline volume fraction, $X_c$, was evaluated from the Raman scattering spectrum was the 514.5-nm line of Ar$^+$ ion laser.

**Results and Discussion**

Fig. 2 shows the topological images of the poly-Si thin films are compared to the local current maps as a function RMS roughness of based-textured substrate (a) $\sigma=85$nm, (b) $\sigma=42$nm, (c) $\sigma=2$nm respectively, and the thickness of poly-Si thin films is kept 2. The scanned area was a 2 $\mu$m square and a half of which is shown. The scale bars are markers for the topological height and the current magnitude. The surface topography shows a monotonous increase in the surface roughness, i.e., the maximum height and the lateral length of the half-spherical region to be assemblages of some grains increase as $d$ increases.
The local current maps of the samples as shown in Fig. 2, homogeneous current flow is found for the samples with RMS based-textured subtracted $\sigma=2\text{nm}$ that shows majority high current around 200nA occupancy the image and then decrease when RMS based-textured subtracted increase continuously.

Figure 3 summarizes (a) the RMS roughness of the poly-Si surface, (b) Crystallinity and (c) the average local current estimated from the images in Fig. 2, as a function RMS roughness of based-textured substrate, $\sigma$. As found in Fig. 3 (a), with increasing $\sigma$, the surface roughness monotonously increases. In contrast, in the Fig 3 (c) the average current rapidly decreases by one orders of the magnitude with increasing $\sigma$. Also we found in Fig. 3 (b) that the crystallinity decrease as the average current rapidly decrease. Reduce the crystallinity implies that more the amorphous phase occurred in poly-Si layer, increase the amorphous phase make increasing the conductivity, this can explain the average current decrease in highly textured substrate. Another report confirms this that poly-Si that deposited in highly textured substrate occurs collisions between the columnar crystal with neighbor grains, and then creates a grain boundary and related defects [6, 8, 9, 12, 13, 15]

![Fig. 2: Surface Morphology (left), and Local Current (right) images as a function as a function of RMS Roughness Based-substrate (a) $\sigma=85\text{nm}$, (b) $\sigma=42\text{nm}$ and (c) $\sigma=2\text{nm}$ respectively.](image-url)
Conclusions

A series investigation has been formed to find correlation between local electric current, and crystallinity on polycrystalline Silicon (poly-Si) thin films for solar cells produced by very high frequency (VHF) plasma enhanced chemical vapor deposition as function of textured substrate using a conductive scanning probe microscope (SPM). This investigation revealed that conductivity of the poly-Si layer proportional with the crystallinity of poly-Si. Where poly-Si with rich of crystallinity show has low conductivity where more current can flow. Otherwise, poly-Si with poor of crystallinity show has high conductivity and difficult current can flow in poly-Si layer.

Fig. 3: Local Average Current (a) Crystallite (b) and RMS Roughness of surface (c), as a function of RMS Roughness Based-substrate.
References

[1] Wenhao Chen, Thien N. Truong, Hieu T. Nguyen, Christian Samundsett, Sieu Pheng Phang, Daniel MacDonald, Andres Cuevas, Lang Zhou, Yimao Wan, Di Yan, "Influence of PECVD deposition temperature on phosphorus doped poly-silicon passivating contacts", Solar Energy Materials and Solar Cells, Volume 206, (2020), Page 110348.

[2] Jia Liu, Bin Liu, Xisheng Zhang, Xiaojia Guo, Shengzhong (Frank) Liu, Improvement of crystallinity for poly-Si thin film by negative substrate bias at low temperature, Thin Solid Films, Volume 629, (2017), Pages 90-96.

[3] Subhashis Samanta, Debajyoti Das, Nanocrystalline silicon thin films from SiH4 plasma diluted by H2 and He in RF-PECVD, Journal of Physics and Chemistry of Solids, Volume 105, (2017), Pages 90-98.

[4] Takuya Matsui, Hitoshi Sai, Adrien Bidiville, Hung-Jung Hsu, Koji Matsubara, Progress and limitations of thin-film silicon solar cells, Solar Energy, Volume 170, (2018), Pages 486-498.

[5] Takuya Matsui, Michio Kondo, Advanced materials processing for high-efficiency thin-film silicon solar cells, Solar Energy Materials and Solar Cells, Volume 119, (2013), Pages 156-162.

[6] R. Muhida, T. Kawamura, T. Harano, M. Okajima, T. Toyama, H. Okamoto, S. Honda, H. Takakura, Y. Hamakawa, Crystal growth of polycrystalline silicon thin films for solar cells evaluated by scanning probe microscopy, Journal of Non-Crystalline Solids, Volumes 338-340, (2004), Pages 682-685.

[7] Takuya Matsui, Riza Muhida, Tomohiro Kawamura, Toshihiko Toyama, and Hiroaki Okamoto, Microstructural dependence of electron and hole transport in low-temperature-grown polycrystalline-silicon thin-film solar cells, Appl. Phys. Lett. 81, (2002), Page 4751

[8] Toshihiko Toyama, Hiroaki Okamoto, Structural and electrical studies of plasma-deposited polycrystalline silicon thin-films for photovoltaic application, Solar Energy, Volume 80, Issue 6, (2006), Pages 658-666.

[9] R. Muhida, A. G. E. Sutjipto, Afzeri, T. Toyama, H. Okamoto, Relationship between average slope of textured substrate and poly-Si thin film solar cells performance, Materials Research Innovations, Volume 13, (2009), Pages 246-248.

[10] Takuya Matsui, Masaharu Tsukiji, Hiroyuki Saika, Toshihiko Toyama, Hiroaki Okamoto, Correlation between Microstructure and Photovoltaic Performance of Polycrystalline Silicon Thin Film Solar Cells, Japanese Journal of Applied Physics, Volume 41, Number 1R, (2002), Page 20.

[11] Shinya Honda, Hideyuki Takakura, Yoshihiro Hamakawa, Riza Muhida, Tomohiro Kawamura, Tomokazu Harano, Toshihiko Toyama and Hiroaki Okamoto, Carrier Transport in Polycrystalline Silicon Thin Film Solar Cells Grown on a Highly Textured Structure, Jpn. J. Appl. Phys. 43, (2004), Page 5955

[12] Riza Muhida, Tomohiro Kawamura, Tomokazu Harano, Masaya Okajima, Takuya Matsui, Toshihiko Toyama, Hiroaki Okamoto, Shinya Honda, Hideyuki Takakura and Yoshihiro Hamakawa, Carrier Transport in Polycrystalline Silicon Photovoltaic Layer on Highly Textured Substrate, Jpn. J. Appl. Phys. 42, (2002), Page 6753

[13] Toshihiko Toyama, Riza Muhida, Tomokazu Harano, Tsuyoshi Sugano, Masaya Okajima and Hiroaki Okamoto, Solid Phase Crystalization in Initial Growth Region of Polycrystalline Silicon Layer During Deposition at 180°C by Plasma Chemical Vapor Deposition, Jpn. J. Appl. Phys. 42, (2003, Page L1347
[14] R. Muhida, T. Matsui, Takahiro Kawamura, T. Harano, T. Toyama, H. Okamoto, Shoichiro Honda, H. Takakura, Y. Hamakawa, Correlation between Microstructure and Electronic Property of Solar-Grade Poly-Si Thin-Films Deposited on Textured Substrates, Solid State Phenomena, Vol. 93, (2003) Page 115-120.

[15] R. Muhida, Age Sutjipto, T. Matsui, T. Toyama, H. Okamoto, Measuring the Electronic Properties of Poly-Si Thin Film Solar Cells Deposited on Textured Substrate, Proc. 2006 IEEE 8th International Conference on Properties & applications of Dielectric Materials, Page 309. DOI: 10.1109/ICPADM.2006.284178