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Low-temperature fabrication of silicon films by large-area microwave plasma enhanced chemical vapor deposition

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Abstract

A novel designed microwave PECVD system with large-area microwave plasma source is employed for the feasibility study to grow thin silicon films at low temperature. With the total area being 25 cm × 30 cm, three sets of array antenna composed by many copper rods with adjustable length are employed to couple the microwave power into the deposition chamber. A RF power source is employed to induce a negative bias on the substrates. High purity (99.99%) SiH_4, H_2, and Ar are introduced as reaction gases, and ultrasonically cleaned glasses are used as substrates. Silicon films with grain sizes about 80∼100 nm are successfully deposited at temperatures below 82 °C. Further studies will focus on the modification of the system design so as to reach the goals to deposit silicon films with improved crystallinity, larger grain sizes, and more uniformity over the large area.

Keywords: Large-area microwave plasma; Low-temperature fabrication silicon films; PECVD; RF bias

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) and polycrystalline silicon (poly-Si) thin films are major materials applied in fabricating Thin film transistor (TFT) and thin film solar cell devices [1,2]. As compared with a-Si thin films, poly-Si thin films have great potential in fabricating TFT exhibiting higher speed for the production of TFT–LCD with higher resolution and better quality. Low-temperature poly-Si (LTPS) TFT with 100 times higher carrier mobility than that of a-Si TFT are usually prepared from a-Si thin films fabricated by PECVD at lower temperature (200∼400 °C) and then followed up by several post-treatment techniques [3–6]. Due to the lower post-treatment temperature (200∼400 °C), relatively inexpensive materials such as glass or even plastic sheets instead of quartz can be used as substrates to fabricate poly-crystalline silicon thin films, making the cost-down of LTPS–TFT LCD in mass production become more promising. However, in order to reach further cost-down for mass production of LTPS–TFT LCD, the direct fabrication of large-area LTPS thin films at an even lower temperature and higher deposition rate will be an important breakthrough, especially when thinner glasses and plastic sheets with lower thermal stability and larger area are used as substrates for the new generation LTPS–TFT LCD production.

Traditional microwave sources have been extensively applied for processes such as plasma etching, plasma cleaning, and thin film deposition in semiconductor and electronic device fabrication due to their higher plasma densities and higher deposition rates compared with DC- and RF-sources. However, with the traditional system design of microwave PECVD (M-PECVD), it is impossible to deposit uniform thin films at low temperature and have large area as required by new generation TFT–LCD mass production. Therefore, the development of the large-area microwave sources is an essential start-point to offer a solution for the mass production of LTPS–TFT LCD. Several groups had reported the new designs of the large-area microwave sources [7–20]; two groups among those had installed proper magnets with special arrangements to become large-area ECR sources [19,20]. However, ECR

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microwave PECVD system has to be operated under lower system pressure, which results in lower deposition rates and higher cost for mass production.

For the surface-wave excited microwave plasma, the basic configuration is the long thin surface-wave plasma column [7] with diameter either comparable to or smaller than the skin depth of microwave (about 1~2 cm). The planar microwave plasma source is accomplished by a plasma column array.

Besides the transmission line field applicator as described in [7], slot antenna field applicator is also used to excite large-area microwave plasma. Two kinds of slot antenna geometries are designed to accomplish top-wall excitation [8–11], or sidewall excitation plasma source [12–15]. For top-wall excitation configuration, Sugai et al. [8] and Nagatsu et al. [9] discussed the effect of four different slot antenna structures on the productions of the large-area plasma. A 40-cm diameter large-area plasma source producing high-density plasma with a uniform electron density more than 10^{11} cm^{-3} was developed via the combination of the transverse and the longitudinal slot antenna structures. It was employed for hydrogenated amorphous carbon films deposition at a system pressure of 200 mTorr at room temperature [10]. However, the deposition rate and the uniformity of film thickness were not indicated in their study. Shimatani et al. [11] proposed a ring slot antenna structure to develop a large-area plasma source. The best results obtained in their study are that the effective plasma region equal to 24 cm in diameter and the uniformity of ion current density equal to ±3%. There are no further studies about the applications of this plasma source for thin films deposition.

For the sidewall excitation configuration, Korzec et al. [12] developed three types of slot antenna (SLAN) plasma sources. The discharge region is 4, 16, and 66 cm in diameter for μ-SLAN, SLAN I, and SLAN II, respectively. Details about the principle of SLAN operation are also described by Korzec et al. [12]. Films deposition are carried out in μ-SLAN and SLAN I systems, the results show that the maximum deposition rate is 2.5 μm/min for silicon containing (SiO_x) films [13] and 30 nm/min for DLC films [14], respectively. The large-area SLAN II plasma source with maximum ion concentration more than 10^{12} cm^{-3} and ionization degree about 0.1% is mainly used for surface cleaning applications [15]. However, there are also no further studies about SLAN II because of the non-uniformity of the plasma.

Besides the slot antenna configurations described above, Kaiser et al. [16] and Walker et al. [17] developed a Duo-Plasmaline microwave plasma source that produced linearly extended plasma in a pressure range from 3.75×10^{-2} to 3.75 Torr for etching, cleaning, and thin film deposition. According to the different microwave power and system pressure, the linear plasma region could be extended up to several meters [16]. Two-dimensional plasma could be obtained via a linear plasma source array. The characterization of the quartz-like films deposited using this system revealed good homogeneity in terms of deposition rate over an area equal to 10 cm × 50 cm [17]. Based on the Duo-Plasmaline principle, Schlemm et al. [18] developed a magnetic field (non-ECR) enhanced large-area microwave plasma source to fabricate silicon nitride films for solar cell applications. Silicon nitride films with deposition rate equal to 150 nm/min and uniformity in thickness better than 5% over the area equal to 10 cm × 50 cm can be obtained in their system. However, since two microwave power supplies are required for each Duo-Plasmaline to reach better uniformity, the system is more expensive.

Murai et al. [19] developed a disc-shaped ECR plasma source with a plasma region 16 cm in diameter for film deposition. However, this plasma source could only produce a uniform plasma region about 10 cm in diameter. Tada et al. [20] developed a microwave launching system composed by special arrangement of metal bars and dielectric plate for both circular and rectangular plasma sources. Furthermore, Tada installed the proper magnets with special arrangements and created large-area ECR plasma system. The circular ECR source can produce a uniform O_2 plasma region 10 cm from the magnet's surface, 30 cm in diameter, and with an ion current density within ±3.8% of uniformity at a pressure of 3 mTorr. The rectangular ECR source can produce a large-area plasma region with dimensions of 40 cm × 50 cm; however, the stability and the uniformity of the ion current density still needed improvement.

In this paper, a newly designed M-PECVD system with Adjustable Array Antenna (Triple-A) large-area plasma source is employed. Different from the design concept reported [7–20], the Triple-A plasma source with copper rods arrays functioning as power dividers can produce large-area and low-temperature microwave plasma. In addition, by adjusting the number of the antenna elements and the design of arrays, this plasma source can be easily scale-up. Up to now, this Triple-A plasma source is mainly used for plasma etching and cleaning application in microelectronic industries. Since the low-temperature large-area thin film deposition becomes more and more important in the optoelectronic industry, the main goal of this study is to explore the application potential of this Triple-A plasma source in large-area thin film deposition at a low temperature for LTPS–TFT. Some preliminary results to deposit silicon thin film at 82 °C are reported in this paper.

2. Experimental

Silicon films were synthesized in an Adjusted Array Antenna (Triple-A) large-area M-PECVD system. A 2.45-GHz microwave was transmitted by a rectangular wave-guide and then coupled into a three-channel array antenna via three copper tubes (main antenna) that are 45 cm in length and 8 mm in diameter. The three-channel array antenna composed of 180 small copper rods (antenna

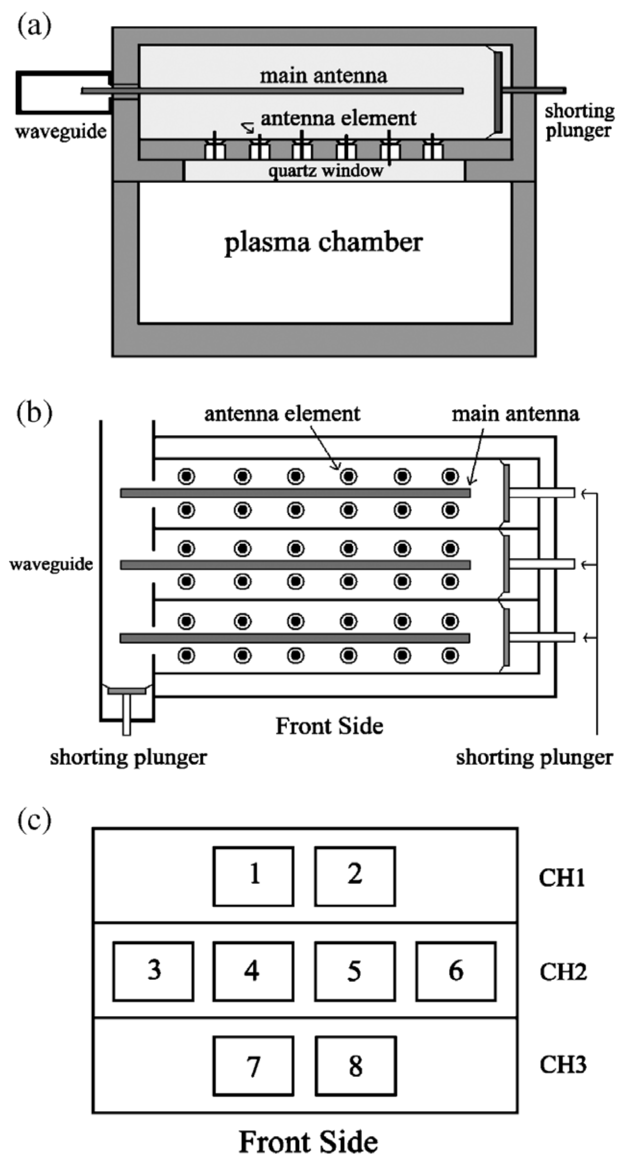

Fig. 1. The schematic drawings of (a) side view and (b) top view of the Triple-A microwave plasma source; and (c) the substrates positioning on holder.

elements) which are 23∼29 mm in length and 2 mm in diameter. In each channel, 60 antenna elements were arranged in four rows (that is, each row having 15 copper rods) and every 2 cm apart. Each channel has an area equal to 168 cm^2 (28 cm × 6 cm). The schematic representation of the Triple-A plasma source is shown in Fig. 1(a) and (b). The microwave power was radiated and passed through the quartz windows below the array antenna (25 cm × 30 cm) into the deposition chamber (40 cm × 45 cm) to generate plasma. An RF power supply was employed to induce a negative bias on the substrate. High purity (99.99%) SiH_4, H_2, and Ar mixtures were introduced as reaction gases. Glass plates were selected as substrates and were ultrasonically cleaned with acetone, followed by a thorough rinsing with de-ionized water and then blown dry with filtered N_2 before being transferred into the deposition chamber. The distance between the substrate holder and the quartz windows was kept at 10 cm. Eight substrates were mounted on a holder (30 cm × 35 cm) in the projected region of the three-array antenna channels as shown in Fig. 1(c). The reaction gases were monitored by MKS mass flow controllers and introduced separately into the deposition chamber. The system pressure was determined by an MKS Baratron transducer and kept constant by an automatic pressure controller. The deposition temperature was roughly measured by THERMAX temperature indicators attached to the backside of the substrate holder.

Prior to the film deposition, the system was evacuated to a base pressure less than 3 mTorr. Ar-plasma cleaning was performed on substrates for 1 h under a system pressure

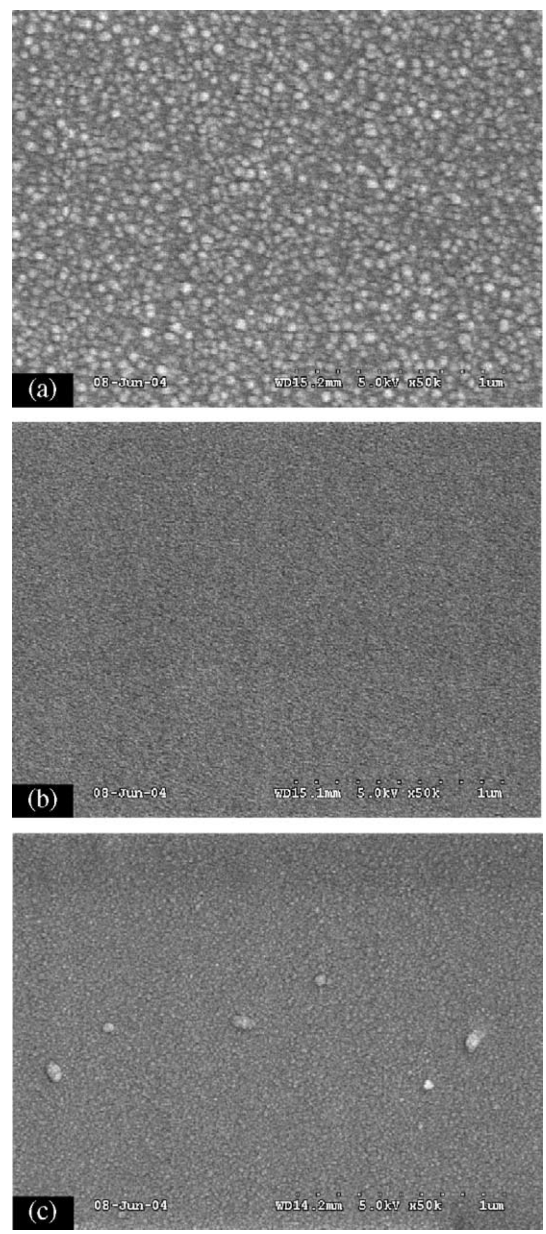

Fig. 2. The SEM micrographs of silicon films obtained under various W_2 input (a) 15 W, (b) 30 W, and (c) 40 W.

equal to 1 Torr and a microwave power equal to 600 W. For all experiments, the SiH_4 and the Ar flow rates were kept at 1 and 50 sccm, respectively.

In this study, the films obtained at position #5 were selected for discussion, unless otherwise mentioned. The surface morphology and roughness of the films were examined by Hitachi S-4300 field emission scanning electron microscopy (FE-SEM) and NT-MDT Solver P47 atomic force microscopy (AFM), respectively. A MAC Science M21X X-ray diffractometer (XRD) was employed to examine the microstructure of the films. The thickness of the films was determined by α-step measurements.

3. Results and discussion

To explore the potential of the low-temperature large-area thin film deposition in this Triple-A M-PECVD system, silicon films deposition were carried out. By adjusting the positions of the shorting plungers of each channel and the rectangular waveguide, the microwave power could be coupled into the antenna region and passed through the quartz windows. Since arcing occurred in the antenna region and the main antenna burned when the microwave power increased over 800 W, all the experiments were carried out at 600 W and 700 W to avoid the damages of system. Moreover, since the system pressure were automatically controlled under fixed system pressure of 1 Torr for all the experiments, the plasma became unstable when the H_2 flow rate exceeding 30 sccm due to higher pumping rate. Under these limitations of the existing system, the experiments were operated only under the operating conditions to sustain stable plasma.

For the preliminary studies, the microwave power was selected as 600 W, and the deposition period was fixed at 4 h. Before RF power applied to the glass substrates, silicon films with poor adhesion were deposited only on the surfaces of quartz windows facing the deposition chamber under all the system operating conditions chosen. In order to attract the positive ions toward glass substrates, the RF power selected as 15, 30, 40 W was applied to substrates. After RF power applied, silicon films were successfully deposited on the substrates. Fig. 2 showed the SEM micrographs of silicon films deposited at position #5 under various RF power (W_2) input. Grains of about 50 nm in size were observed under RF power equal to 15 W (Fig. 2(a)); whereas grains with smaller sizes about 10 nm were

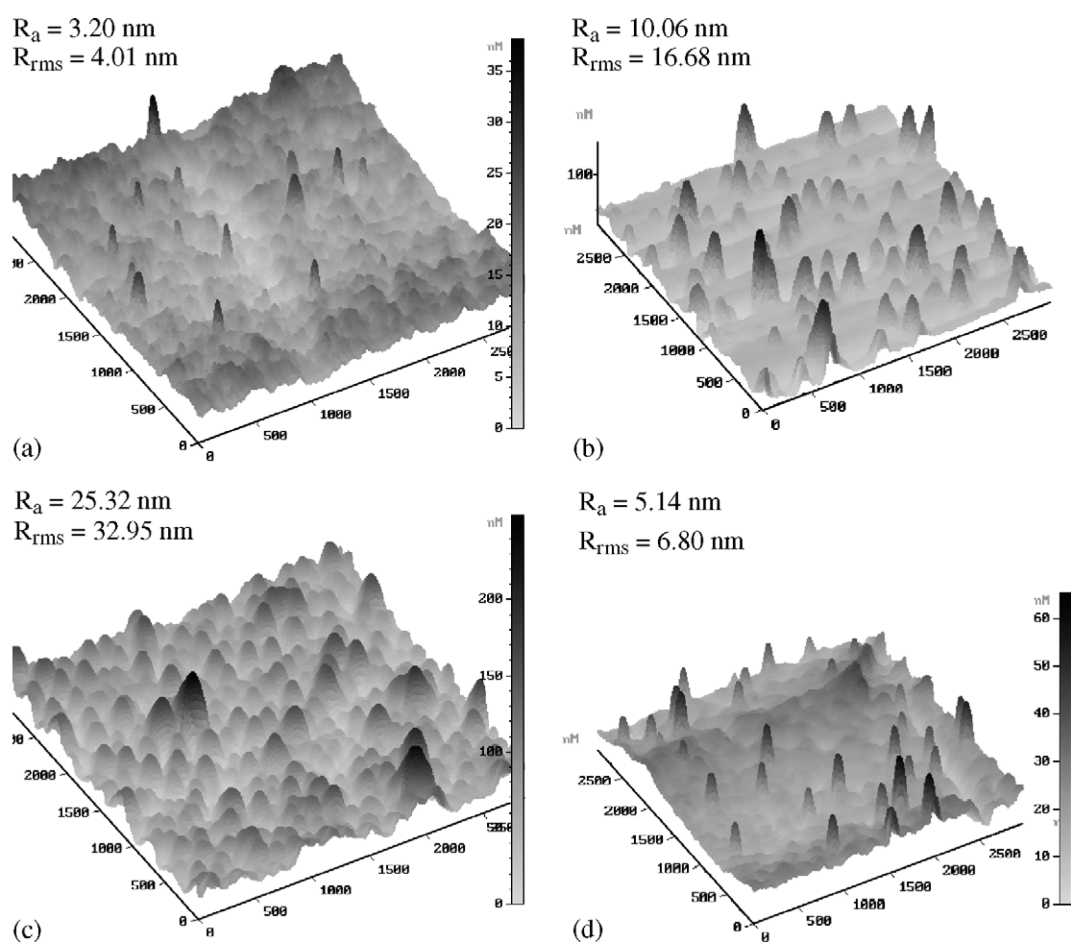

Fig. 3. The AFM topographies of silicon films obtained under F_{H_2} equal to (a) 10 sccm, (b) 20 sccm, (c) 25 sccm, and (d) 30 sccm.

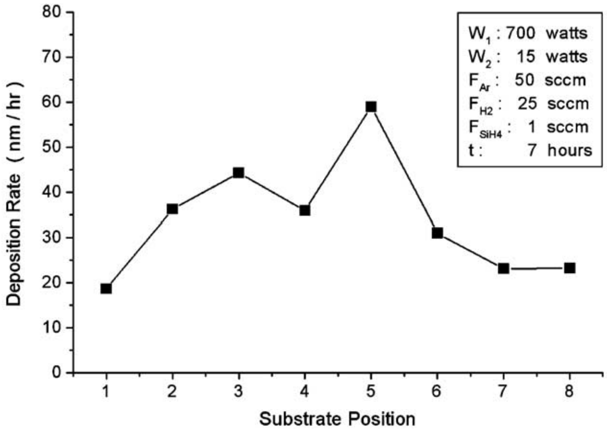

Fig. 4. The profile of deposition rates of silicon films.

observed under higher RF powers (Fig. 2(b) and (c)). As the RF power increased, the roughness (root mean square) of those films obtained by AFM improved from 4.01 nm (Fig. 2(a)), 2.71 nm (Fig. 2(b)), to 0.49 nm (Fig. 2(c)); which means that the grains in films become smaller as RF power increased. Under 40-W RF bias power, the temperature of the quartz windows and the substrate holder were 110 °C and 82 °C, respectively. From the above-mentioned results, it is concluded that as a stronger negative bias is induced on the substrate, the ion bombardment becomes more severe and the plasma temperature becomes higher which are not favorable for film deposition and large grains' growth. Therefore, RF power for the following experiments was fixed at 15 W.

Furthermore, in order to investigate the effect of H_2 on the improvement of the quality of silicon films, the flow rate of H_2 (F_{H_2}) was varied from 10 to 30 sccm with W_1 fixed to 600 W and W_2 fixed to 15 W. The deposition rate decreased from 33.1 to 24.3 nm/h as the F_{H_2} increased due to the competing process of the hydrogen plasma to etch the weak Si–Si bonds away from the surface of the growing Si-film [21,22]. In addition, from the AFM topographies shown in Fig. 3, it is obvious that films become rougher as the F_{H_2} increased from 10 to 25 sccm; however, they become smoother as F_{H_2} increased to 30 sccm. Since the film obtained under F_{H_2} equal to 25 sccm appeared to have more uniform and larger grains, further studies are based on the same operating conditions except that higher microwave power (700 W) and longer period of deposition (7 h) are applied. The profile of deposition rates of this last experiment is shown in Fig. 4 and the SEM micrographs of the films obtained at four different positions (#1, 4, 5, 8) on the substrate holder are shown in Fig. 5.

Fig. 4 reveals that the plasma of this existing system is not uniform and the maximum deposition rate equal to 59 nm/h was obtained at position #5. Although the uniformity of the silicon films still needed to be improved, more than 70% of the substrate holder is observed to have coated with silicon films. Fig. 5 shows that the silicon films obtained at four positions have similar morphologies except the density

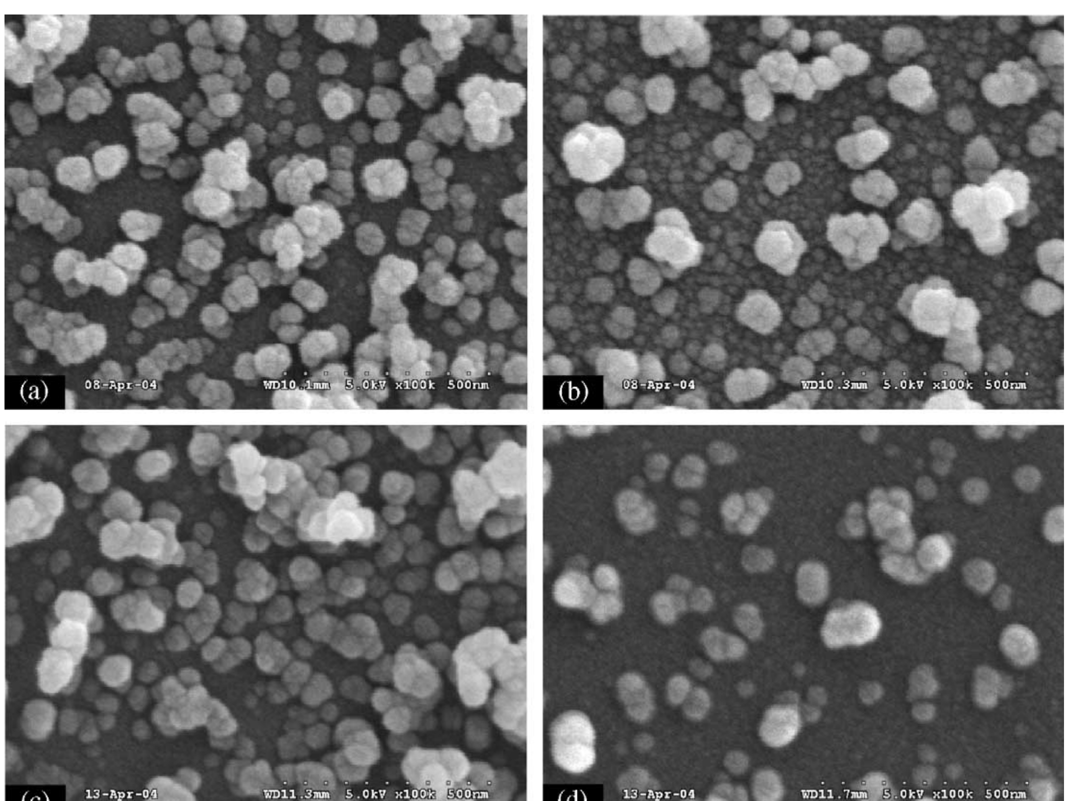

Fig. 5. The SEM micrographs of films obtained at different positions: (a) position #1, (b) position #4, (c) position #5, and (d) position #8.

of grains appeared to be lower on films deposited at position #8, which may be due to lower deposition rate. The morphologies clearly show that there are smaller grains (about 10 nm) at the lower level and larger grains (about 80~100 nm) at the upper level.

However, from XRD analyses of all the films obtained in this study, no clear characteristic diffraction peaks were observed which means the crystallinity of the silicon films still needs to be improved. Although the quality of the silicon films are far from the required application in LTPS–TFT LCD industries, our main goal to explore the potential of the existing Triple-A large-area microwave etching system in new application to fabricate silicon thin film has been reached. More R&D works are required to improve the coupling of the microwave power to the deposition chamber so that higher power than 800 W can be applied to grow better quality silicon films in a more uniform plasma environment.

4. Conclusion

Silicon thin films with grain size about 80~100 nm have been successfully fabricated in an Adjustable Array Antenna (Triple-A) large-area M-PECVD system at temperatures below 82 °C. The Triple-A microwave plasma source has showed great potential for low temperature and large-area thin film deposition. To reach our goal to deposit silicon films with improved crystallinity, larger grain sizes, and acceptable uniformity over the large area for LTPS–TFT LCD application, further work such as system modification and microwave coupling improvement will be carried out.

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