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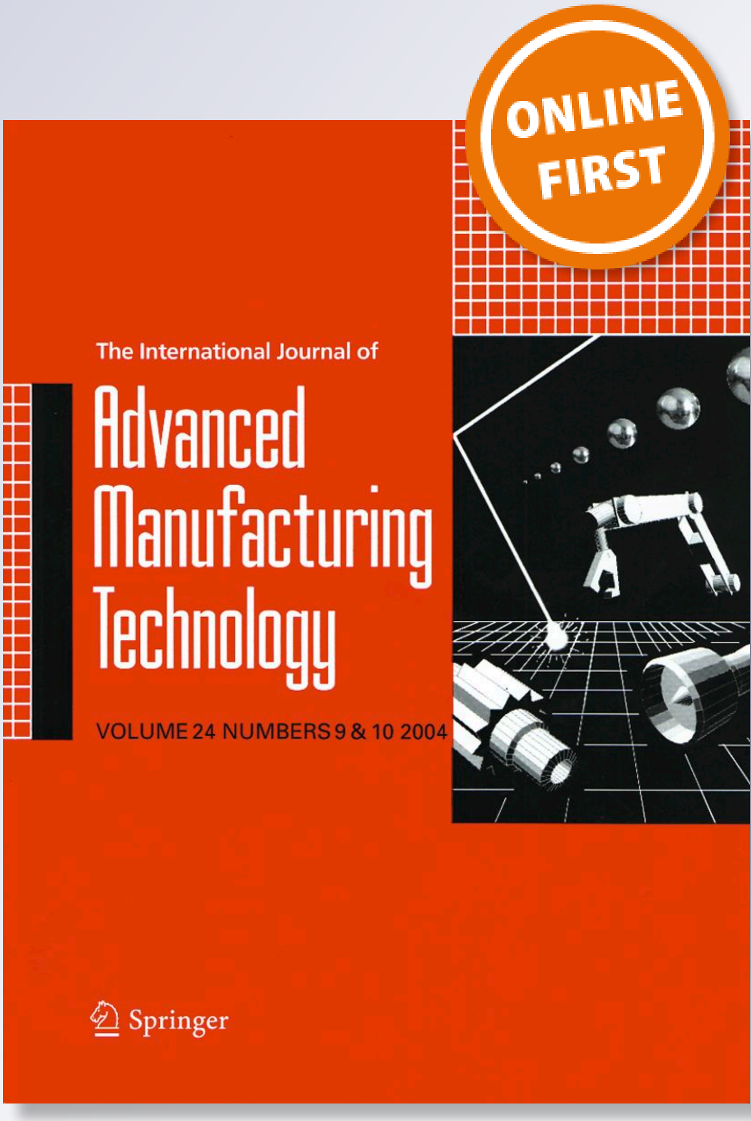

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ORIGINAL ARTICLE

Effects of laser parameters on optoelectronic properties of polycrystalline silicon films prepared by two-step annealing process

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Abstract A two-step method combining furnace and laser annealing is proposed for improving the electrical and optical properties of amorphous silicon thin films on glass substrates. It is shown that the optical transmittance of the as-deposited silicon film increases from 27 to 31% following furnace annealing at 600 °C. However, the electrical resistance is too high to be measured using a four-point probe. The sheet resistance can be reduced to 270 kΩ/□ by annealing the as-deposited film using an ultra-violet (UV) laser. However, the resistance is still too high for TFT applications. The as-deposited silicon film is first furnace annealed at 600 °C for 12 h and then annealed using a UV laser with a laser power of 41 mW and a scanning speed of 60 mm/s. The optical transmittance and sheet resistance of the annealed film are found to be 29% and 1.17 kΩ/□, respectively. The X-ray diffraction (XRD) results suggest that the improved optical and electrical properties are the result of an amorphous-to-crystalline transformation of the silicon microstructure.

Keywords Silicon film · Laser · Annealing · Crystallization

1 Introduction

Silicon can exist in a variety of forms, including single crystalline, polycrystalline, and amorphous [1]. Polycrystalline silicon (poly-Si) films have good field-effect mobility and are thus used in many optoelectronic applications, such as thin film transistors (TFTs), solar cells, and active matrix organic light emitting displays (AMOLED) [2, 3]. For TFTs, a higher electron mobility within the active channel facilitates the integration of high-speed circuits and improves the pixel switching capability in display applications. In practice, the electron mobility within poly-Si structures is governed by the grain size. For example, previous studies have shown that the field-effect mobility increases with an increasing grain size due to a greater scattering of the electrons at the grain boundaries [4]. Notably, the microstructure of Si thin films determines not only their electrical properties but also their optical properties. Consequently, the problem of optimizing the Si microstructure through appropriate deposition and post-processing procedures has attracted significant attention in the literature. Amorphous Si thin films are generally deposited on low-cost substrates such as glass using plasma-enhanced chemical vapor deposition (PECVD). However, the electrical properties of polycrystalline silicon films are better than those of amorphous silicon films [5]. An amorphous-to-polycrystalline transformation can be obtained by post annealing process. The defect density would be reduced by annealing the deposited film at temperatures of more than 900 °C. However, the underlying glass substrate is easily damaged at such high temperatures. While this problem can be avoided by using quartz substrates rather than glass substrates, this greatly increases the fabrication cost. Consequently, various alternative silicon deposition and post-processing methods have been proposed, including solid phase crystallization (SPC) [6, 7], excimer laser annealing (ELA) [8, 9], metal induced crystallization (MIC) [10–13], and rapid thermal annealing (RTA) [14].

Solid phase crystallization allows for the formation of Si crystalline grains at a relatively low temperature of 600 °C. However, the grains have a high density of defects, such as

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twins and stacking faults. These defects can be reduced by increasing the annealing temperature. However, by doing so, the use of a glass substrate is precluded. Zhang et al. [14] used RTA to crystallize precursor a-Si:H films on quartz substrates. The results showed that the poly-Si films were completely crystallized given an annealing temperature of 900 °C. Furthermore, the crystallized grains were obtained after only a few seconds, thereby significantly reducing the fabrication time of the poly-Si film compared to such methods as the conventional furnace method. However, due to the high annealing temperature, the RTA method cannot be applied to glass substrates. Poly-Si films can be realized at temperatures as low as 450 °C using the MIC method because the precipitates formed act as nuclei sites for crystallization in the thermal annealing process. However, the films contain a large number of impurities, which serve as sources of leakage and therefore degrade the device performance [10–12, 15, 16]. Compared to the methods described above, excimer laser annealing enables the crystallization of poly-Si films to be achieved at temperatures as high as 900 °C but only few micrometer thicknesses is annealed. This temperature can be easily reached in solid phase with laser irradiation and provides a high temperature process without damaging the glass substrates according to the short irradiation time. As a result, it is compatible with the use of low-cost glass substrates. The limitation of ELA method is high cost for the equipment and high power density easily results in the thermal stress [17]. The proposed two-step process can lower the equipment cost and thermal stress. Accordingly, the present study proposes a two-step crystallization process in which the as-deposited Si film is first processed by furnace annealing to release the gas content and is then UV laser annealed in order to reduce the defect density. The optimal laser annealing parameters are determined by evaluating the electrical, optical and structural properties of the various samples using a four-point probe technique, spectrophotometry, X-ray diffraction (XRD), and optical microscopy (OM).

2 Experimental

Amorphous thin films with a thickness of 40 nm were deposited on glass substrates using a PECVD system with a power of 150 W, a pressure of 460 mTorr, a SiH_4 flow rate of 150 sccm, and a temperature of 380 °C. The as-deposited samples were processed using four different treatments: (1) furnace annealed at 600 °C for 12~24 h; (2) annealed using a green laser (532 nm, Matrix 532-7) with a focused spot size of 50 μm; (3) annealed using a UV laser (355 nm, Coherent AVIA 355-7000) with a focused spot size of 16 μm; and (4) furnace annealed at 600 °C for 12 h and then UV laser annealed. In order to identify the optimal processing conditions, the UV laser annealing process was performed using a pulse repetition rate of 20~100 kHz, laser scanning speeds in the range of 20~70 mm/s, and laser powers in the range of 27~41 mW.

The sheet resistance of the various samples was measured using a four-point probe method. Meanwhile, the optical transmittance was measured using a UV-VIS-IR spectrophotometer (Lambda 35). The crystalline properties of the samples were investigated using an X-ray diffractometer (Bruker D8) with Cu-Kα radiation. Finally, the surface morphologies of the various samples were examined using optical microscopy (OM).

3 Results and discussions

Figure 1 shows the transmittance of the as-deposited Si film and the films furnace annealed at 600 °C for various intervals (12~24 h). As shown, the optical transmittance of the as-deposited Si film is around 27% at a wavelength of 550 nm. Following annealing for 12 h, the optical transmittance increases to 31%. However, as the annealing time is further increased to 24 h, the transmittance reduces to approximately 22%. The results presented in Fig. 1 show that, given an appropriate annealing time, furnace annealing improves the optical transmittance of the Si film. However, irrespective of the annealing time, the electrical resistance was found to be too high to be measured using the four-point probe (i.e., >100 MΩ/□). Accordingly, the as-deposited Si film was annealed using a green laser system with various pulse repetition rates, laser powers and scanning speeds. As shown in Fig. 2, the transmittance increased to approximately 35% under an illumination wavelength of 550 nm given a pulse repletion rate of 20 kHz, a laser power of 50 mW and a scanning speed of 40 mm/s. The electrical activation is verified by the observed increase in the crystalline component of the Si structures resulting in higher transmittance [18]. However, the sheet resistance of the annealed film was still too high to be

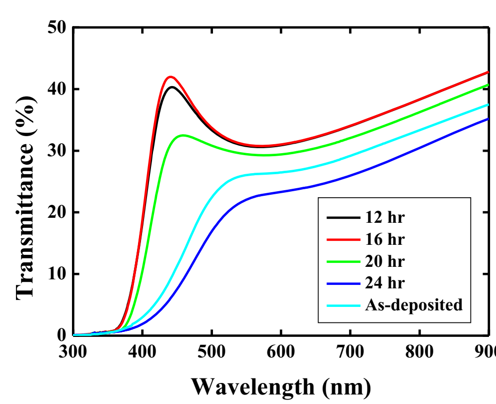

Fig. 1 Optical transmittance of Si films furnace annealed at 600 °C for 12~24 h

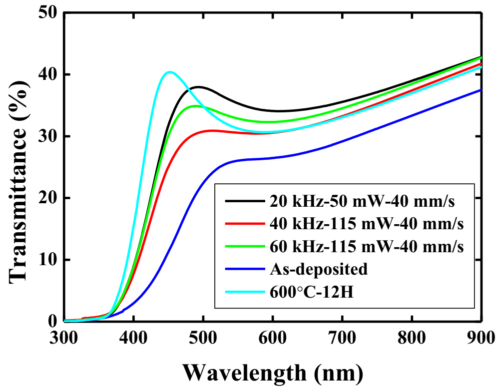

Fig. 2 Optical transmittance of Si films processed by green laser annealing

measured. Accordingly, the as-deposited films were annealed using a UV laser system.

Table 1 shows the sheet resistance values obtained for the films annealed with various UV laser powers and scanning speeds. Note that the repetition rate is 100 kHz in every case. It is apparent that, with the exception of the maximum scanning rate (40 mm/s) and scanning power (38 mW), the UV annealing process yields an effective reduction in the sheet resistance compared to that achieved using the green laser annealing process. For a constant scanning speed, the resistance increases with an increasing power. Moreover, for a constant power, the resistance increases with an increasing scanning speed. Thus, the minimum sheet resistance (270 kΩ/□) is obtained using the lowest scanning speed (20 mm/s) and lowest power (21 mW). The improvement in the electrical property of Si film can be attributed to the reduction of defect density [19].

Although the UV annealing process reduces the sheet resistance of the as-deposited Si film, the minimum sheet resistance value (i.e., 270 kΩ/□) is still too high for TFT applications. Accordingly, a two-step process was performed in which the as-deposited Si film was first furnace annealed at 600 °C for 12 h and then UV laser annealed using various laser powers and scanning speeds. Figure 3 shows the sheet resistance measurements obtained for the different samples. In general, the results show that the two-step post-processing operation yields a lower electrical resistance than the one-step UV laser annealing process (i.e., no prior furnace annealing). For example, given the same laser annealing conditions of 27 mW and 40 mm/s, the sheet resistance of the one-step

Table 1 Sheet resistance of Si films annealed with different UV laser powers and scanning speeds

	21 mW	27 mW	38 mW
20 mm/s	270 kΩ/□	459 kΩ/□	1453 kΩ/□
30 mm/s	378 kΩ/□	392 kΩ/□	9.9 MΩ/□
40 mm/s	612 kΩ/□	1139 kΩ/□	–

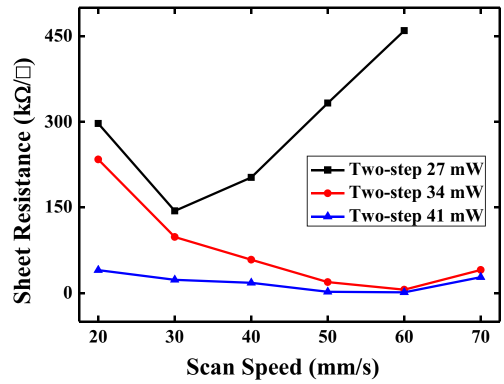

Fig. 3 Sheet resistance of two-step annealed Si films

sample is around 1139 kΩ/□ (see Table 1), while that of the two-step sample is 203 kΩ/□. Furthermore, for a laser power of 41 mW and a scanning speed of 60 mm/s, the sheet resistance of the two-step sample reduces to just 1.17 kΩ/□. Therefore, the electrical property of the Si film was effectively improved using a two-step process.

Figure 4 shows the optical transmittance values of the one-step and two-step annealed samples processed with different laser powers and scanning speeds. The results clearly show that the two-step annealing process leads to a significant improvement in the transmittance. For example, given a laser power of 27 mW and a scanning speed of 40 mm/s, the transmittance of the one-step sample is just 20%, whereas that of the two-step sample is around 32%. Furthermore, for lower values of the laser power (27 and 34 mW), the transmittance of the two-step sample increases with an increasing scanning speed. Consequently, a transmittance of 33% can be obtained using a power of 34 mW and a scanning speed of 70 mm/s. Overall, the results presented in Figs. 3 and 4 show that the two-step process improves both the electrical properties of the as-deposited Si film and the highest optical transmittance and lowest sheet resistance of the annealed film are found to be 35% and 1.17 kΩ/□, respectively.

Figure 5 shows the XRD patterns of the as-deposited Si sample, a one-step Si sample (600 °C/12 h), and a two-step Si sample (600 °C/12 h; 41 mW, 60 mm/s). The XRD pattern

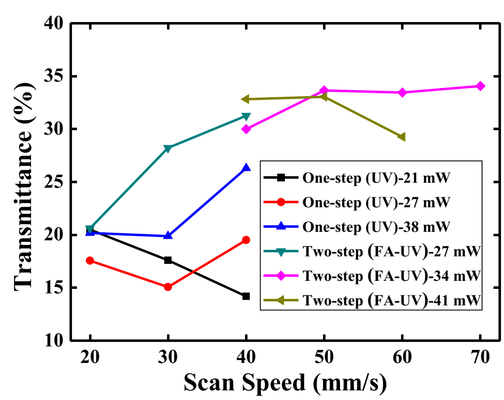

Fig. 4 Optical transmittance of one-step and two-step annealed Si films

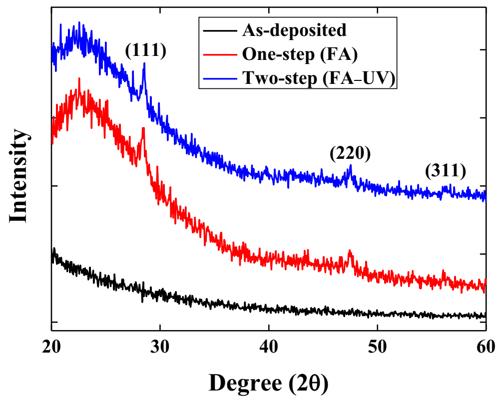

Fig. 5 XRD patterns of various Si films for a one-step Si sample (600 °C/12 h), and a two-step Si sample (600 °C/12 h; 41 mW, 60 mm/s)

of the as-deposited Si film has no prominent peaks, and hence, it is inferred that the film has an amorphous structure. For the one-step annealed sample, peaks are observed corresponding to the (111), (220), and (311) planes. Park [20] also reported a-Si is completely crystallized into poly-Si at above 600 °C. Below 600 °C, no obvious XRD peak was observed. With increasing the annealing temperature up to 600 °C, the crystallization of a-Si films occurs and the surface becomes uniform. The small crystallites agglomerate into larger grains with elimination of defects around crystallite boundaries [21].

In other words, the UV laser annealing process results in the formation of a polycrystalline state. The intensity of the peaks is enhanced in the XRD spectrum of the two-step sample. Thus, it is inferred that the dual furnace annealing/laser annealing process results in a further improvement in the crystalline properties of the Si film. It is further inferred that the transformation from an amorphous state to a polycrystalline state is directly responsible for the improved electrical and optical properties of the two-step sample. The two-step heating is sufficient to provide the driving force for atomic rearrangement in terms of the short- and/or long-range order.

Figure 6 presents OM images of the samples annealed with scanning speeds of 20 and 60 mm/s and laser powers of 27, 34, and 41 mW. It is seen that the sample annealed with a scanning speed of 20 mm/s contains a greater number of voids than that annealed at 60 mm/s. The speed of these processes depends on laser power density and the wavelength, as well as on the thickness of Si layer [22]. Further, vasa [23] reported that laser fluence between 300 and 500 mJ/cm^2 is required for crystallization and the ablation threshold is estimated to be above 500 mJ/cm^2. Our experimental fluence is from 300 to 440 mJ/cm^2. Therefore, operating a lower speed (~20 mm/s), accompanied agglomeration on the surface was easily observed. In other words, voids are induced in the Si surface as the local input thermal energy increases (i.e., the overlapping ratio increases). The presence of these voids increases the sheet resistance and decreases the transmittance.

4 Conclusions

Silicon films were deposited on glass substrates using a PECVD system and then annealed at 600 °C for 12 h. The annealing process increased the optical transmittance at a wavelength of 550 nm from 27 to 31%. However, the electrical resistance was too high to be measured. Accordingly, the as-deposited films were annealed instead using a green laser system. The optical transmittance was found to be 32% under

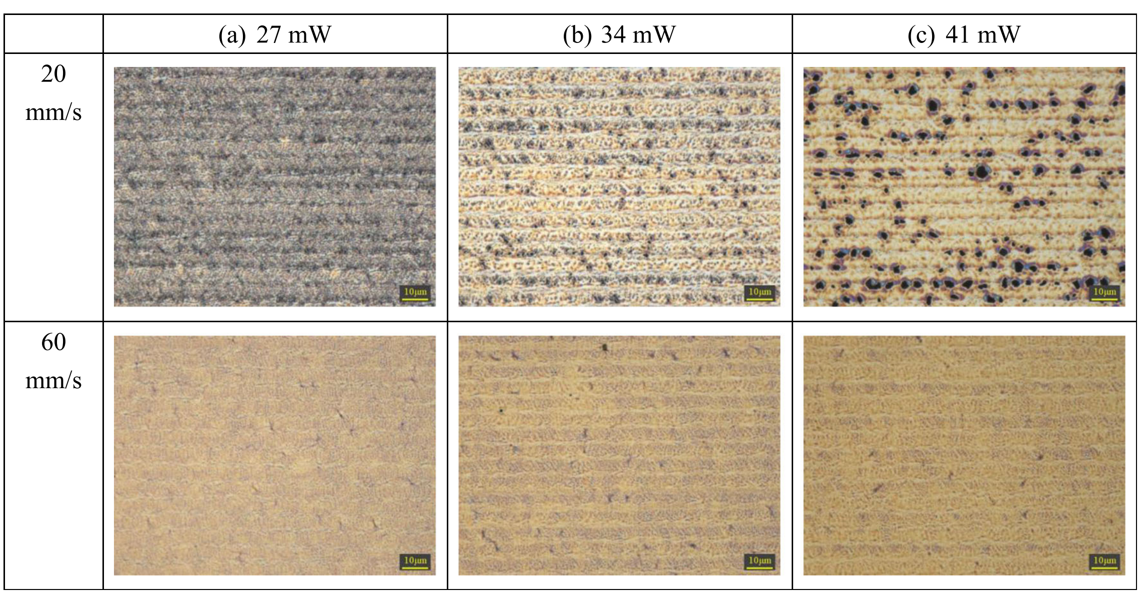

Fig. 6 OM images of two-step annealed Si films processed with scanning speeds of 20 and 60 mm/s and laser powers of **a** 27 mW, **b** 34 mW, and **c** 41 mW

an illumination wavelength of 550 nm. However, the electrical resistance was still too high to be measured. Consequently, the as-deposited films were annealed using a UV laser system with various laser powers and scanning speeds. A sheet resistance of 270 kΩ/□ was obtained using a laser power of 21 mW and a scanning speed of 40 mm/s. To further improve the optoelectronic properties of the as-deposited Si samples, a two-step furnace annealing and UV laser annealing process was performed. Given optimal settings of the annealing parameters (600 °C/12 h; 41 mW, 60 mm/s), the sample was found to have an optical transmittance of 29% and a sheet resistance of 1.17 k Ω/□. The XRD and OM results showed that the improved optical and electrical properties of the sample are due to an amorphous-to-polycrystalline transformation of the Si microstructure during the two-step annealing process.

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