High rate deposition of poly-Si thin films at low temperature using a new designed magnetron sputtering source

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Abstract

We have deposited poly-Si thin films on Si(100) and glass substrates at growth temperature of below 400°C using a newly developed high rate magnetron sputtering method. To improve the sputtering yield and the growth rate, a high power (10–30 W/cm²) magnetron sputtering system was designed and constructed. Based on the results of computer simulation, we built up the magnetron sputter source with unbalanced magnetron and Si ion extraction grid. The maximum deposition rate reached was 0.35 mm/min due to a high ion bombardment. This is five times higher than that of conventional sputtering methods, and the sputtering yield was also increased up to 80%. The best film was obtained on Si(100) surface using Si ion extraction grid under 9.0×10⁻³ torr of working pressure and 11 W/cm² of the target power density. The electron mobility of the poly-Si film grown on Si(100) at 400°C with ion extraction grid was 96 cm²/Vs. In this study, however, we found that the target power density is a more important factor than working pressure to influence the growth rate, mobility, and the film quality. During sputtering, moreover, the characteristics of Si sputter source were also analyzed with an in situ Langmuir probe method and optical emission spectroscopy. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

After LeComber et al. [1] reported the first amorphous hydrogenated silicon (a-Si/H) TFT, many laboratories started the development of an active matrix LCDs using a-Si/H TFTs formed on glass substrate. With increasing the display area and pixel density of TFT-LCD, however, high mobility TFTs are required for pixel driver of TFT-LCD in order to shorten the charging time of the pixel electrodes. The most important of these drawbacks is the electron mobility of a-Si, which is the speed at which electrons can move through each transistor. The problem of low carrier mobility for the a-Si/H TFTs can be overcome by introducing polycrystalline silicon (p-Si) thin film instead of a-Si/H as a semiconductor layer of TFTs [2]. The electron mobility (i.e. 0.3–0.7 cm²/Vs) of a-Si is roughly two orders of magnitude lower in mobility than p-Si, and p-Si is two orders of magnitude lower than single crystal silicon [3,4]. p-Si is the most promising material for obtaining such high mobility TFTs for pixel drivers. Moreover, the peripheral driver circuits can be integrated on the same substrate. Therefore, p-Si has gained increasing interest and has been investigated by many researchers [2,5–7]. Recently, fabrication of such p-Si TFT-LCD panels with VGA pixel size and monolithic drivers has been reported [8]. In particular, fabricating p-Si TFTs at a temperature much lower than the strain point of glass is needed in order
to have high mobility TFTs on large-area glass substrate, and the monolithic drivers will reduce the cost of TFT-LCDs. The conventional methods to fabricate p-Si films are low pressure chemical vapor deposition (LPCVD) as well as solid phase crystallization (SPC), pulsed rapid thermal annealing (PRTA), and eximer laser annealing (ELA) [9–11]. However, these methods have some disadvantages such as high deposition temperature over 600°C, small grain size (< 50 nm), poor crystallinity, and high grain boundary states. Therefore, the low temperature and large area processes using a cheap glass substrate are impossible because of high temperature processes. To enhance crystal properties, SPC is a more useful method to increase the grain size than the as-deposited p-Si thin film by LPCVD [10]. However, it needs a long time annealing at high temperature over 600°C. On the other hand, even though up to now LPCVD and sputtering always produced poor crystallinity and relatively small grain size that depends on the thickness of the p-Si layer, these methods can fabricate p-Si film below 450°C [11].

Among them a magnetron sputtering method by pulse d.c. was our focus to improve the crystallinity and grain size of p-Si thin film grown at low temperature, because pulse d.c. magnetron sputtering has many advantages of high growth rate, low temperature deposition, and good reproducibility. In this study, therefore, we tried to make high quality p-Si thin films at temperature as low as 400°C using a newly designed magnetron sputter source with Si ion extraction grid. Since our developed sputter source can operate at low voltage and high current, it shows high deposition rate and direct p-Si deposition on the large-area glass substrate. Moreover, the sputter source has high sputtering yield, when an ion extraction grid was applied, resulting in high Si ion mobility.

2. Experimental

Experiments were carried out using a homemade sputtering system with newly developed high rate and high power magnetron sputter source. Fig. 1a shows the schematic diagram of high rate sputtering system with an unbalanced high power magnetron sputter source developed for the high rate deposition of p-Si thin film. We designed and constructed the sputter source with high target power density capability, that is, the sputter source can operate under the extreme condition such as ultra high vacuum (< 10^-5 torr), high current (10–30 mA/cm²), and low voltage (100–1000 eV). Before construction, a magnetic field simulation was first carried out using a computer program in order to improve the sputtering yield and the growth rate. Based on the results of computer simulation, we built up the high power Si magnetron sputter source that has unbalanced magnetrons both inside and outside of the chamber. The most homogeneous magnetic field distribution was observed when we applied the magnetic field of 300 G into either the inner or the outer magnetic coils, respectively. Noticeably, in the case of balanced magnetic coil, inhomogeneous magnetic field has been induced as a result of our computer simulation. However, when we took an unbalanced magnetic coil system with $I_{\text{inner coil}}/I_{\text{outer coil}} = 1:2$, the best homogeneous magnetic field was obtained, suggesting that the sputtering yield together with growth rate can be increased as much as factor of 2. This is in good agreement with the previous report published by Musil et al. [12]. In this study, however, we found that with adapting an ion extraction grid located between the Si target and substrate, the deposition rate and sputtering yield can additionally increase three or four times higher than that in the case of balanced magnetic coils. Fig. 1b shows the principle of Si ion extraction grid taken in our system. The enhancement of deposition rate and plasma density by attachment of the Si ion extraction grid can be explained as follows. The attachment of the grid with negative electric potential will reflect electrons and constrict them between grid and target surface, and thereby increase the electron density. Such enhancement of electron density will then increase the collision probability of electrons with neutrals including Ar and silicon vapor, and promoting ionization of Ar and silicon vapor. Sputtering rate of target surface will then be improved by higher flux Ar ion bombardment. Consequently the silicon vapor flux increases with high ion density. Such combined effect of high vapor flux and ion extraction by the grid will contribute to the enhancement of the deposition rate of the film. The maximum deposition rate and sputtering yield obtained in this study using the newly designed sputter source were 0.35 μm/min and 80%, respectively. This is five times higher than that of conventional sputtering methods.

We used a pulsed d.c. that has 3.333 kHz of frequency and 50% of duty ratio to improve the crystallinity and grain size of p-Si thin film grown at low temperatures below 400°C. Si(100) and Corning 1737 glass were used as substrates, and the substrate was heated by either heater or plasma in the temperature range between 300 and 400°C. The substrate temperatures were measured by using an optical pyrometer. The general growth conditions of p-Si thin films were $5 \times 10^{-4} - 3 \times 10^{-2}$ torr of working pressure, 300 ~ 400°C of deposition temperature, and ~650 V of bias voltage on the Si ion extraction grid. The distance between the target and grid was maintained at 50 mm while that between the substrate and target was kept at 100 mm. The as-grown p-Si thin films were characterized with XRD, XPS, and Raman spectroscopy, and the film thickness was obtained by the α-step profilier and
cross-sectional SEM. The electrical resistivity and electron mobility of the as-grown p-Si thin films were also measured using the four-point probe method and Hall measurement. Moreover, during sputtering, the characteristics of Si sputter source were also analyzed with in situ Langmuir probe method and optical emission spectroscopy (OES) to understand the gas phase reaction in the plasma.

3. Results and discussion

OES is a powerful tool for controlling the sputtering process and for optimizing both the p-Si film layers properties and the deposition process. In this study, therefore, we used the OES as a qualitative in situ plasma diagnostic method. Fig. 2a,b shows the optical emission spectra of Si ion obtained with or without ion extraction grid under different target power densities of (a) 3 W/cm² and (b) 7 W/cm². Three different OE spectra were observed at 633.4, 634.7, and 637.1 nm. By comparison these experimental data with the possible theoretical transition, we identified these OE peaks as following. The first peak at 633.4 nm is attributed to the Si transition array of 3p⁴→3p⁵P⁵P, whereas the remaining peaks at 634.7 and 637.1 nm are mainly contributed to a Si⁺ ion transition array of 3s²4s–3s²(3S)4p, respectively. In Fig. 2a,b, the emission intensities of all appearing peaks were increased with increasing the target power density. Fig. 2c shows the plots of the emission intensity changes measured experimentally by OES with or without Si ion extraction grid as a function of target power densities. From the plots of Fig. 2c, we found that the negatively biased grid played an important role in enhancing the plasma density of Si ions, resulting in high growth rate (see also Fig. 4) and high mobility. This indicates that it is possible to make the p-Si thin films with high electron mobility at very low temperature such as 300°C on the large-area of substrates. The working pressure is also...

Fig. 1. (a) Schematic diagram of high rate sputtering system with newly developed unbalanced high power magnetron sputter source for poly-Si thin film deposition. (b) Principle of silicon ion extraction using a negatively biased grid.

Fig. 2. Optical emission spectra of Si ion obtained under different target power densities of (a) 3 W/cm² and (b) 7 W/cm² with or without ion extraction grid. (c) Changes of measured optical emission intensity as a function of target power densities.
influenced in the plasma intensity. With increasing the working pressure of $5 \times 10^{-4}$ to $3 \times 10^{-2}$ torr, the intensity of OE spectra also increased, indicating that the higher the working pressure the higher the growth rate. However, at a higher working pressure above $3 \times 10^{-2}$ torr, we could not find a distinct effect of the Si ion extraction grid. This suggests that our developed sputter source is quite proper for the p-Si film deposition under the extreme condition such as high vacuum, low temperature, high current, and low voltage ranges since the unbalanced magnetron source can operate nicely even with a high power density of 10–30 W/cm².

Fig. 3a,b show the XRD patterns of the as-grown p-Si thin films deposited on Si(100) substrates at 400°C without Si ion extraction grid (a) and with Si ion extraction grid (b) under a deposition condition of working pressure $9 \times 10^{-3}$ torr and target power density of 11 W/cm². In Fig. 3a, one strong diffraction peak that is attributed to Si(302) phase is observed at $2\theta = 40^\circ$ as well as some small diffraction peaks, suggesting a highly oriented polycrystalline film in the [302] direction. However, thicker polycrystalline film with higher electron mobility and higher growth rate than that of Fig. 3a was obtained from the as-grown p-Si film grown with the grid under the same growth condition. Two strong diffraction peaks of Si(302) and Si(220) are shown in Fig. 3b, signifying high quality p-Si film. The electrical resistivity and electron mobility obtained from those films were $1.3 \, \Omega$/cm and 40 cm²/Vs for the p-Si film grown without the grid, and $1.5 \times 10^{-1} \, \Omega$/cm and 96 cm²/Vs for the p-Si film deposited with the grid, respectively. These results suggested that, in order to get a p-Si film with both high rate and high mobility, the Si ion extraction grid is very important, especially for the large-area deposition, because the grid can increases the ionization bombardment probability, resulting in high amounts of silicon vapor flux and silicon ion density. In the case of p-Si thin film growth on a large (< 4 inch) glass substrate area at 300°C using the grid, however, only a relatively thin, poor crystalline p-Si thin film than that grown on Si(100) was obtained. This means that further experiments are required to make thick, high quality p-Si films on large-size glass substrates. A cross-sectional SEM image, as shown in Fig. 3c, shows a very sharp
interface between p-Si layer and Si(100) substrate, indicating good adhesion and homogeneous film in the depth. The film thickness was approximately 1.2 μm, depending on the target power density rather than the working pressure.

Fig. 4a shows the variation of p-Si deposition rate as a function of target power density. All data were obtained from the p-Si thin films grown on large-area glass substrates at 300°C with Si ion extraction grid. It shows that with increasing the target power, the growth rate was increased. The maximum deposition rate reached was approximately 0.35 μm/min, when the target power was maintained at 21 W/cm². This is five times higher than that of conventional sputtering method, and the sputtering yield also increased from 70 to 80%. To compare the effect of the grid, we grew the p-Si films under the same deposition condition of working pressure (1 × 10⁻⁴ torr) and target power density (15 W/cm²). Fig. 4b shows the effect of Si ion extraction grid more distinctly. This indicates that, under the same deposition condition, the technique of applying an ion extraction grid will be a very useful method to obtain the p-Si thin films with high mobility and high growth rate on large-area glass substrates.

4. Conclusions

Highly oriented p-Si thin films have been deposited on Si(100) and glass substrates at growth temperature in the range of 300–400°C using a newly developed high rate and high power sputtering source with Si ion extraction grid. Based on the results of computer simulation, we designed and constructed the p-Si sputter source that has unbalanced magnetron (I_{inner coil}/I_{outer coil} = 2:1) with a magnetic field of 300 G. The best film was obtained on Si(100) substrate using Si ion extraction grid under a working pressure of 9.0 × 10⁻³ torr and a target power density of 11 W/cm². The maximum deposition rate and sputtering yield of the new sputter source are 0.35 μm/min and 80%, respectively. This is five times higher than that of the conventional sputtering method, resulting in high electron mobility. The electron mobility of the p-Si film grown on Si(100) at 400°C with the grid shows 96 cm²/Vs. In the case of p-Si thin film growth on a large-size glass substrate, however, a p-Si thin film with poor crystallinity and low mobility was observed at 300°C. Moreover, during sputtering, the characteristics of the Si ion source were also analyzed, and we found that the target power density is a more important factor to influence the growth rate, mobility, and film quality than the working pressure.

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