Low Temperature Polysilicon Thin-Film Transistors on Flexible Substrates

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Abstract: *We fabricated low-temperature polycrystalline silicon thin-film transistors (poly-Si TFTs) on flexible substrates using sputtered amorphous Si (a-Si) precursor films. The a-Si precursor films were deposited by using rf-magnetron sputtering system with argon-helium mixture gas to minimize the argon incorporation into the Si film. The a-Si films were laser annealed by using XeCl excimer laser and a four-mask-processed poly-Si TFT was fabricated with fully self-aligned top gate structure. The fabricated pMOS TFT showed field-effect mobility up to 63.6 $cm^2/V{\cdot}s$, on/off ratio of 10^5, and threshold voltage of -1.5 V.*

Keywords: poly-Si TFT, flexible substrate, excimer laser, sputter.

Introduction

Polycrystalline silicon thin-film transistors (poly-Si TFTs) are widely used in active-matrix flat panel displays as pixel switching devices and also as peripheral drive circuit elements. The monolithic integration of drive circuits into the panels reduces the external interconnections to the panels and improves the form/factor of the displays [1]. Generally, the poly-Si TFTs are fabricated on glass substrates by using amorphous silicon (a-Si) films deposited by plasma-enhanced chemical vapor deposition (PECVD) or low-pressure chemical vapor deposition (LPCVD). However, a-Si deposited by PECVD at low temperature (<150^{o}C) contains a considerable amount of hydrogen atoms (10~20 at%) and these hydrogen atoms incorporated in Si films cause ablation during the laser irradiation. To eliminate the film-ablation problem, a dehydrogenation process (~400^{o}C) is usually carried out before the laser annealing to remove the hydrogen atoms. However, the plastic substrates have glass transition temperatures below 300^{o}C meaning that thermal dehydrogenation process may not be employed in plastic systems. We used a sputtering process to deposit the a-Si films which results in a very low concentration of hydrogen atoms incorporated in the Si films (1~2 at%).

Using the sputter deposited a-Si precursor films we fabricated low temperature poly-Si TFTs on a flexible plastic substrate. The a-Si precursor films were deposited by rf-magnetron sputtering system with argon-helium mixture gas to minimize the argon incorporation into the Si film. The a-Si films were then laser annealed by a XeCl excimer laser and a four-mask-processed poly-Si TFT was fabricated with fully self-aligned top gate structure. The fabricated pMOS TFTs showed field-effect mobility of 63.6 $cm^2/V{\cdot}s$.

Experimental

The direct fabrication of poly-Si TFTs on a polymer substrate causes severe problems during the device fabrication process. In particular, significant amounts of stress are induced in the deposited inorganic layers due to thermal expansion mismatch between the polymer substrate and the inorganic layers [3]. This indeed generates cracks in the inorganic layers, leading to failure of the transistor device. In order to minimize the stress induced during the fabrication process, the substrate should be pre-annealed before any inorganic material deposition step. Here, the substrate was pre-annealed at 180℃ (for polyethersulfone; PES) or 250℃ (for polyarylate; PAR) in a vacuum oven before the fabrication. Also, to evaluate the shrinkage rates of annealed polymer substrates, the substrates were stored in the vacuum oven at 150℃.

The a-Si precursor film was deposited on 600-nm-thick SiO_2 buffer layer by using a sputtering system with argon/helium gas mixture. The a-Si film was then laminated onto a glass substrate by using a thin adhesive film and irradiated by XeCl excimer laser (λ = 308 nm) with a flat top beam profile. The pulse duration and the beam size of the laser were 35 ns and 45 x 0.2 mm^2, respectively. After defining AlNd gate electrode (sputter, 200-nm thick) and gate insulator (PECVD, 200-nm thick), an ion-shower process was carried out to dope the Si layer and activation was done again by laser. Then, 400-nm-thick interlayer dielectric was deposited and a contact hole was defined. Finally, 300-nm-thick AlNd source and drain electrodes were deposited and patterned.

Results and Discussion

One of the disadvantages of using polymer substrates instead of using glass is the large shrinkage rates during a thermal cycling process. Upon heating a polymer material, structural changes take place, which can be divided into a reversible part controlled by coefficient of expansion (CTE) and an irreversible part given by coefficient of shrinkage [4]. Although the CTE mismatch between the polymer and inorganic films induces considerable stress in the film-substrate system, the shrinkage of polymer may also give a critical limitation to TFT fabrication, since it is an irreversible process. In order to reduce the effect of irreversible shrinkage during TFT fabrication, the substrates must be annealed before the process starts. Figure 1 shows the shrinkage rates of PAR and PES substrates with various annealing conditions. The shrinkage rates were noticeably decreased with annealing time of more than 60 hours. For PAR substrates, the rates decreased from 30 ~ 50 ppm/K

to less than 2 ppm/K and, for PES, the rates decreased from 180 ~ 200 ppm/K to 2 ppm/K, which are in the acceptable range for the TFT fabrication process.

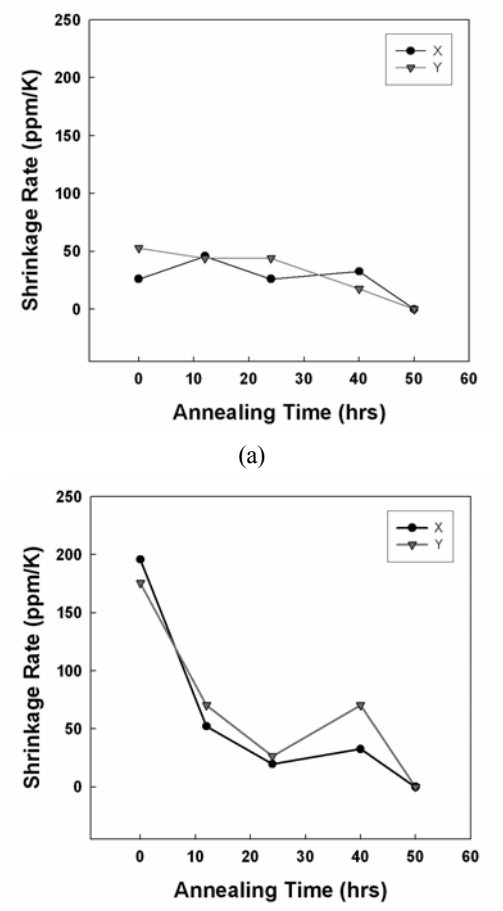

Figure 1. Shrinkage-rate variation of (a) PAR and (b) PES substrates as a function of annealing time.

During the sputtering of a-Si films, sputtering gas atoms such as argon and helium are incorporated in the film *via* collision of sufficient kinetic energy ions or neutrals with the growing film [5]. According to T. Voutsas *et. al.*, the energetic argon atoms are responsible for undesirable argon incorporation in the film and microstructural modification of the as-sputtered Si films, and they suggested that in order to minimize the gas incorporation problem a lighter inert gas such as helium can be substituted for argon [6]. Also, according to D. P. Gosain *et. al.*, argon content within the a-Si film causes explosive argon gas effusion during the laser crystallization and damages the Si films [7].

In this research, the a-Si film was coated by sputtering in argon/helium mixture atmosphere to minimize the argon impurity concentration in the a-Si film. The argon impurity concentration in the a-Si film was controlled by adjusting the argon/helium mixture ratio and working pressure. Although the a-Si film deposited in the argon/helium contains a small amount of helium, helium is easily effused out of Si by the leading edge of the laser beam and no critical problems occur due to helium while crystallizing the a-Si films [8].

Figure 2 shows the Rutherford backscattering spectrometry (RBS) spectra and the in-film argon concentrations with different argon/helium mixture ratios. The measured spectra were simulated to evaluate the argon concentrations in the Si films. The random RBS spectra were obtained by using 2.003-MeV He^{++} beams with incident beam charge and current of 20 μC and 20 nA, respectively. The figure shows a clear relationship between the argon concentration and the argon/helium ratio. Particularly, with an argon/helium ratio of 2:20, the argon concentration in the film was determined as 1.6 at%, whereas with an argon/helium ratio of 2:5, the argon concentration was 6.0 at%.

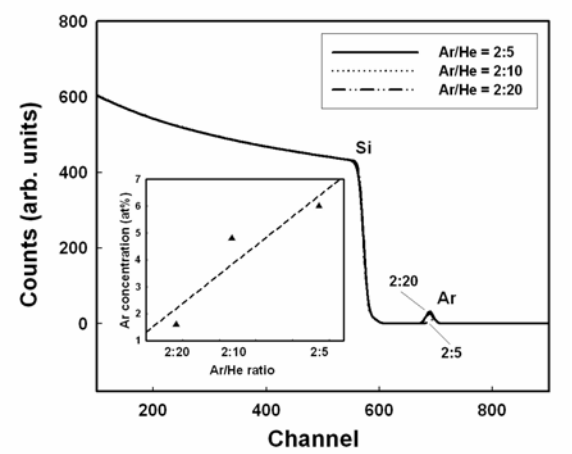

Figure 2. RBS spectra of sputtered a-Si films with different argon/helium mixture ratios. The inset shows the relevant argon concentrations.

The a-Si film was laser-annealed in vacuum atmosphere at room temperature. During the laser annealing process, ablation of Si film was observed in samples with buffer layer thickness less than 400 nm, whereas ablation was not occurred when the buffer layer thickness was thicker than 600 nm. This suggests that there exists a critical buffer layer thickness when using a substrate having low thermal stability since the substrate experiences an extremely high temperature increase during the short period of the laser annealing process. Figure 3 shows transmission electron microscopy (TEM) images of poly-Si films irradiated with various energy densities. The grain boundaries are clearly seen in the images, and the grain size increased from 10 nm to 400 nm when the laser energy densities were 200, 267 and 289 mJ/cm^2.

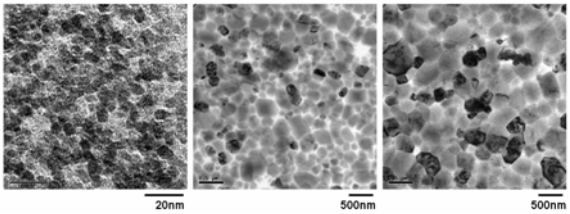

Figure 3. TEM images of laser-annealed poly-Si films irradiated by various laser energy densities.

Ion-implantation or ion-shower doping is widely used in low-temperature poly-Si TFT fabrication to form the ohmic contact between the Si and the source/drain metal layer. The ion-shower doping method is used in this experiment. The doping temperature and acceleration voltage were room temperature and 10 kV, respectively. The ion doses of the phosphorus- and boron-doped films were 1×10^{15} cm^2 and 8.2×10^{15} cm^2, respectively. As displayed in Fig. 4, a rapid decrease of the sheet resistance of phosphorus- and boron-doped films was observed with increasing laser energy density up to 213 mJ/cm^2 and 267 mJ/cm^2, respectively. The decrease of sheet resistance with increasing laser energy density in both cases occurs because the melting depth of the Si film is increased with the laser energy density [9]. Sheet resistances of 470 Ω/sq. for boron doping and 1200 Ω/sq. for phosphorus doping were successfully obtained on polymer substrates and these values are low enough for the source and drain formation in poly-Si TFTs.

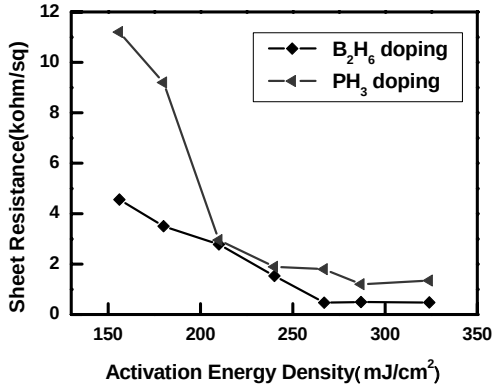

Figure 4. Sheet resistance of n- and p-doped poly-Si film as a function of laser activation energy.

In Fig. 5, the optical microscope image of low-temperature poly-Si TFT fabricated on a plastic substrate is shown and the corresponding transfer characteristic of fabricated TFT is shown in Fig. 6. The pMOS poly-Si TFT showed field-effect mobility of 63.6 cm^2/V·s, on/off ratio of 10^5 and a threshold voltage of -1.5 V.

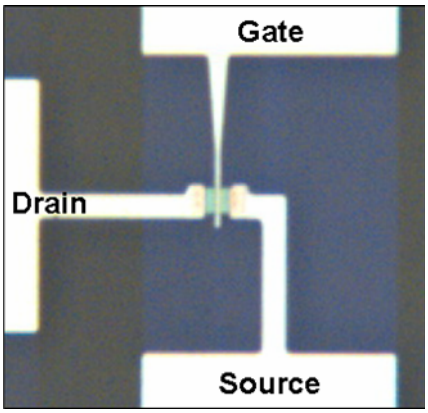

Figure 5. An optical microscope image of low-temperature poly-Si TFT fabricated on a plastic substrate.

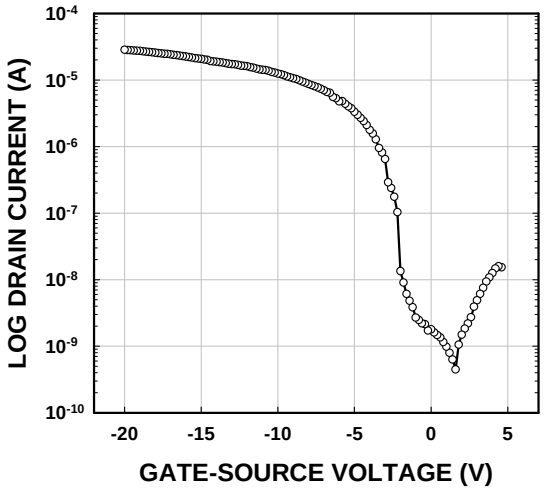

Figure 6. Transfer characteristic of fabricated pMOS poly-Si TFTs on PES substrates.

Conclusions

We successfully fabricated low-temperature poly-Si TFTs on flexible plastic substrates by using sputter-deposited a-Si films and excimer laser annealing process. It was found that the argon impurity concentration was dependent on the argon/helium mixture ratio and the concentration was significantly reduced when the argon/helium mixture ratio was 2 to 20. It was confirmed by the TEM analysis that poly-Si films were formed after the excimer laser irradiation with average grain size of 400 nm when the laser energy density was 289 mJ/cm^2. Four-mask-processed poly-Si TFTs were fabricated with fully self-aligned top gate structure and the fabricated pMOS TFTs showed field-effect mobility of 63.6 cm^2/V·s, on/off ratio of 10^5 and a threshold voltage of -1.5 V.

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