Ion Shower Doping of Polysilicon Films on Polyethersulfone Substrates for Flexible TFT Arrays

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A technique of ion shower doping was performed to form source-drain contacts for polysilicon thin-film transistors (TFTs) on polyethersulfone (PES) substrates. The doped layer was subsequently annealed with an excimer laser to electrically activate the dopant atoms. The doped polysilicon films on the PES substrate showed much higher sheet resistances than those on the glass substrate with the identical doping and activation conditions. Moreover, the plastic substrates is easily heated up and caused a film failure for the prolonged exposure of the ion shower doping. The effective doping time and the resulting ion dose could be increased remarkably by reducing the radio-frequency power as well as by inserting interval pulses for dopants relaxation during the ion doping. As a result, a sheet resistance value as low as 300 ohms/sq, was obtained, which is low enough for a good ohmic contact.

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Manuscript submitted October 10, 2005; revised manuscript received March 29, 2006. Available electronically May 9, 2006.

Experimental

PES sheets 0.5 mm thick were coated with thin, inorganic buffer layers to be used as flexible substrates, as described elsewhere.13 A thick (500 Å) layer of polycrystalline silicon was grown on the substrate by sputtering and was crystallized by an excimer laser annealing (ELA) technique. The PES was chosen for a substrate material because it is known to have the highest temperature-resistance (~200°C) among various translucent and colorless plastic substances. Other light-transmitting polymers, such as polyethylene terephthalate (PET) and polycarbonate (PC), have glass transition temperatures below 110°C. Polyimide can stand up to 400°C, but has a yellow color.15

Phosphorus doping was performed to form source-drain contacts of a TFT, by using an ion shower doping system located at Seoul National University. Figure 1 shows a schematic diagram of the ion shower system. Active dopant ion radicals were generated from a mixture of PH3 and H2 gas by a 13.56 MHz radio-frequency (rf) source. The radicals were then accelerated on to the substrate by a dc bias of 15 kV. The rf power and the doping time were varied to investigate the effect of bombarding ions on the plastic substrates.

The doped layer was subsequently annealed with an excimer laser to activate the dopant atoms electrically. The laser energy density and the number of laser shots were varied and their effects on the sheet resistance were studied.

Results and Discussion

The polysilicon films on plastic substrates usually exhibited lower values of sheet resistance than those on glass substrates. Ion shower doping for 30 s on plastic substrates resulted in sheet resistance values that were much higher than 105 Ω/□, while a sheet resistance of 400 Ω/□ could be achieved on glass substrates.

We attempted a long term thermal annealing at a temperature of 180°C which is slightly lower than the glass transition temperature of the PES substrate. The change in the sheet resistance after thermal annealing is plotted in Fig. 2. As shown in the plot, the sheet resistance decreased with the annealing time up to 12 h. The resistivity of polysilicon films on glass substrates did not show any noticeable change with annealing at this relatively low temperature. This result implies that, in the polysilicon film deposited on plastic substrates, there exist certain microstructural defects associated with the dopant atoms, which can be annealed out with relatively low activation energy.

Park et al. reported that the microstructural damage in the polysilicon films on glass substrate, which was caused by ion implanta-

Thin-film transistors (TFTs), having a polycrystalline silicon film as a channel layer, are used for driving active matrix organic light-emitting display (AM-OLED) devices.1,2 The AM-OLED is a good candidate for flexible displays due to its self-illuminating capability and very wide viewing angle.3 Also, because both the driving electronics and the illuminating layers are integrated on a single substrate, the gap control, which is critical for transmitting correct electronic quality.

Performance of the TFT is greatly affected by the resistance at source-drain regions.3 The silicon layer of those regions must always be doped heavily to realize good ohmic contact between the doped regions and the electrodes as well as small series resistance distributed in these doped regions. Normally, sheet resistance values of source-drain regions below 103 Ω/□ are desired. Also, the ion shower doping technique is widely used to control the contact resistance of the polysilicon TFTs because of its large area capability.8,10 There are several other doping techniques that have been attempted on plastic substrates as well.11,12 However, because the ion shower is the standard process used for polysilicon TFTs on glass substrates, developing a low-temperature doping technique based on the ion shower may facilitate the application of the TFT process architecture to the plastic substrates. Unlike on glass substrates, ion shower doping on plastic substrates has certain technical limitations, such as poor activation efficiency and susceptibility to thermal damage.13

In this paper, a modified ion shower doping was performed on polysilicon films on polyether sulfone (PES) substrates to form source-drain contacts having a low resistivity without thermal damage. Various process parameters that influence the ultimate sheet resistance of the polysilicon film were investigated, and a proper doping process was proposed to obtain sufficiently low resistance.
tion, was responsible for the increase in the sheet resistance at high ion dose. The recovery of the structural damage is a much slower process than the dopant activation. Therefore, a sufficient thermal budget would be required for effective activation annealing. However, in this experiment, the polysilicon films on plastic substrates seemed to behave in a different manner from the foregoing argument.

We compared the degree of crystallinity by using an ultraviolet (UV) reflectance spectroscopy technique after the samples were annealed with an excimer laser for dopant activation. Figure 3 shows the UV reflectance spectra for films doped with various ion doses. White circle, triangle, and square symbols stand for the UV reflectance spectra of the laser-activated films following ion shower doping for 3, 7, and 15 min, respectively. As a reference, a UV spectrum of a film that was doped but not activated was also included, and is represented by black square symbols.

For activated films, the spectra show characteristic peaks at the wavenumbers of approximately 280 and 370 nm. The peak intensity increases with increase in the doping time. However, no noticeable peaks appear for the unactivated film. The degree of crystallinity was estimated by integrating the area under the characteristic peaks and by comparing them with the peaks of a silicon wafer. The peak areas of the samples doped for 3, 7, and 15 min were calculated to be 54, 73, and 86%, respectively, of the single crystal silicon.

The laser energy density used for dopant activation was only 70% of what was used for initial crystallization of the as-deposited silicon films. The UV reflectance data show that the laser activation not only activated the dopant atoms but also led to significant recrystallization of the amorphized film, even at this level of laser energy. This result suggests that the dopant ions may assist recrystallization and grain growth, and the slow damage recovery of the crystalline structure is not responsible for the relatively high sheet resistance on the plastic substrate. Although the acceleration voltage was the same as that used in Park et al.’s experiment, the polysilicon films on PES substrates are in the dose-controlled regime and not in the defect-controlled regime. Therefore, the decrease in the sheet resistance after the long term annealing at 180°C is thought to be associated with some localized defects other than incomplete crystallization, or with local strain caused by the relatively high compliance of the plastic substrate.

Although the thermal annealing decreased the sheet resistance, the annealing time beyond 12 h did not lead to a sufficiently low sheet resistance value to obtain good contact resistance. Also, such a long term annealing is not practical in fabricating the TFT arrays for display devices. Therefore, a very high doping density is usually required, and consequently the doping time must be extended to obtain sufficiently low resistivity values. However, we found that, during the ion shower process, the plastic substrates often suffered structural damage, as shown in Fig. 4. Figure 4a shows a polysilicon film that was blistered, cracked, and finally delaminated during the conventional ion shower doping. This damage is believed to be due to the self-heating caused by the ion bombardment. The orange color of the film indicates that the film was amorphized during the doping. Figure 4b shows undamaged polysilicon film that was re-crystallized during the laser activation following the pulsed ion shower doping. The light squares represent laser-crystallized area and the orange background represents the film left amorphized.

At an rf power of 150 W that was a standard value for doping on glass substrates, the temperature of the film surface rose to a temperature that was as high as 210°C after 30 s from the onset of the ion shower. Ion shower doping was performed at a reduced rf power to verify that the film damage was a consequence of the ion bombardment. Figure 5 shows the sheet resistance values at two different levels of rf power, 100 and 150 W, respectively. Doping for 2 min at 100 W resulted in the sheet resistance values comparable to those doped for 30 s at 150 W. At the rf power of 100 W, the substrate could last much longer inside the doping chamber than at 150 W. After 2 min of doping, the temperature of the film surface increased.

**Figure 1.** Schematic diagram of the ion shower doping system.

**Figure 2.** Change in sheet resistance with additional thermal annealing at 180°C after the laser activation.

**Figure 3.** UV reflectance spectra of the polysilicon films doped by ion shower and activated by subsequent excimer laser annealing. White circle, triangle, and square symbols stand for the laser-activated films following ion shower doping for 3, 7, and 15 min, respectively. Black square symbols are included as a reference and represent the film that was doped for 3 min, but not activated with a laser.
where resistance should be inversely proportional as expected from the dopant activation efficiency remains constant, the sheet resistance changed linearly with a negative slope. However, with an assumption that the dopant activation efficiency might lower the overall resistivity. The degree of crystallinity may affect the sheet resistance according to

\[ \sigma = \frac{L q^2}{kT} n_{\text{eff}} v_0 e^{-\frac{qB}{kT}} \]  

where \( L \) is the grain size, \( n_{\text{eff}} \) the average carrier concentration in poly-Si films, \( v_0 \) the average carrier velocity, \( V_B \) the barrier height.

The dopant-assisted recrystallization was confirmed by observation of the microstructure. Figure 7 shows the TEM images and corresponding electron diffraction patterns for polysilicon films that were doped with various ion doses. Figure 7a corresponds to an as-doped film; the ion shower was performed for 3 min and the TEM image was taken prior to laser activation. The diffuse diffraction ring indicates that the 3 min doping amorphized the polysilicon film. Figure 7b and c show the polysilicon films after laser activation, with doping times of 3 and 15 min, respectively. As the ion dose increased with the doping time, the grains became larger after the laser activation, and more distinct diffraction spots evolved from the ring pattern. Grains larger than 0.1 \( \mu \)m in size were observed in the films doped for 15 min.

Kang et al. reported the recrystallization characteristics of phosphorus-doped polysilicon films amorphized by germanium ion implantation.\(^{20}\) Field-effect mobility increases with increasing grain size and grain size dependence of mobility indicated that the electron conduction is strongly restricted by scattering at the grain boundary.\(^{21,22}\) They attributed the improved grain size to the retardation of random nucleation and the enhancement of grain growth at the presence of dopant atoms.

**Conclusion**

Ion shower doping for polysilicon TFTs was studied for the source-drain contact of TFTs on PES substrates. The polysilicon films on the PES substrate showed much higher sheet resistance. Thermal annealing at 180°C for an extended period up to 12 h decreased the sheet resistance by a factor of one-half to one-third, but was not sufficient to obtain what was required for a good source-drain contact. A relatively high ion dose was required for sheet resistance values below \( 10^3 \) \( \Omega \)cm, but the plastic substrates heated up and caused film failure under prolonged exposure to the ion shower.

The doping time and the resulting ion dose could be increased by reducing the rf power and allowing intervals for relaxation only to 150°C. However, the doping time must be extended to obtain the equivalent sheet resistance at the reduced rf power.

From the above result, the rf power was set to 100 W and the ion shower doping process was divided into cycles consisting of 1 min doping and 2 min relaxation. The doping time was controlled by repeating the cycles by required number of times. Figure 6 shows the sheet resistance values for three different amounts of doping time. As the doping time increased, the average ion dose and the final sheet resistance decreased linearly. A sheet resistance that was as low as 300 ohms/sq. was accomplished.

Note that, as the ion dose increased, the sheet resistance, \( R_S \), changed linearly with a negative slope. However, with an assumption that the dopant activation efficiency remains constant, the sheet resistance should be inversely proportional as expected from

\[ R_S = \frac{L}{t D_n q \mu} \]  

where \( \rho \) is the resistivity, \( t \) is the film thickness, \( D_n \) is the density of activated dopant atoms, \( q \) is the electron charge, and \( \mu \) is the electron mobility. The resistivity change predicted by this equation is indicated by the dotted line in Fig. 6. The decrease in the experimental data is more pronounced than the value (\( \times 1/D_n \)) predicted from the increase in the number of ions incorporated in the high dose regime. Therefore, it may be deduced that either the doping (activation) efficiency or the apparent mobility increases with the doping density. If the increased density of dopant atoms assist recrystallization, either the number of unactivated dopants which are segregated in the grain boundary or in the amorphous region would decrease, or the apparent mobility would be increased by reducing the trap sites, resulting in the decrease of the net resistivity in either case.

As discussed previously with the UV reflectance spectra, the enhanced crystallinity that appeared in the heavily doped samples might lower the overall resistivity. The degree of crystallinity may affect the sheet resistance according to

\[ R_S = \frac{L}{t D_n q \mu} \]

Figure 5. Change in sheet resistance at two different levels of rf power for generating dopant ions.

Figure 6. The Change in sheet resistance and the average ion dose with increase in the doping time. The dotted line indicates the resistivity change predicted by Eq. 1 with constant activation efficiency and mobility.
A sheet resistance as low as $300 \, \Omega/\square$ was obtained, which is low enough for a good ohmic contact. The higher the ion dose, the larger the grain size of the polysilicon film after activated and annealed by an excimer laser.

Acknowledgements

This research was supported by grant no. M102KR010011-04K1801-01111 from the Information Display R&D Center, one of the 21st Century Frontier R&D Programs funded by the Ministry of Science and Technology of the Korean government.

Samsung Advanced Institute of Technology assisted in meeting the publication costs of this article.

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