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Phosphorus Doping by Electron Cyclotron Resonance Plasma for Large Area Poly-Si TFTs

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We have investigated phosphorus doping by an electron cyclotron resonance plasma for application to the poly-Si driving circuits of LCDs or image sensors. The PH_3/He was ionized and accelerated to poly-Si and c-Si substrates with a self bias of ~-220 V. The P concentration as detected by SIMS is ~5×10^{21} cm^{-3} at the surface which decayed to ~10^{17} cm^{-3} within 50~100 nm depth. The film surface is found to be etched during doping which limits the doped depth. The etching is restored by adding a small amount of SiH_4 and the sheet resistance R_s decreases. The optimized R_s as irradiated are ~1×10^5 Ω/□ and 1.7×10^2 Ω/□ for poly-Si and (110) c-Si, respectively.

1. Introduction

An electron cyclotron resonance (ECR) plasma has gained much attention because it is very useful for low-temperature deposition of semiconductor and insulator films, and for fine pattern etching. However, there is little work of doping except that of boron doping for the shallow junctions of LSIs[1]. Large area post doping has become an important technique in fabricating CMOS thin film transistors (TFTs) for the driving circuits of liquid crystal displays (LCDs) or image sensors. The ionization efficiency of ECR plasma is two or three orders of magnitude higher than that of conventional rf plasma. Therefore, more P^+ ions may be produced in place of PH_x^+ ions which may limit the dose of dopant or the quality of doped layer. Also, enlargement of substrate size is considered to be relatively easy for ECR.

We have made fundamental experiments of phosphorus doping into poly-Si by the ECR plasma for the first time, and showed that the ECR plasma doping technique is feasible for large area poly-Si TFTs.

2. Experimental

The schematic cross-section of the ECR plasma apparatus is shown in Fig.1. In the ECR chamber, microwave (2.54 GHz) and magnetic field (875 Gauss) are simultaneously supplied to meet the ECR condition. He-diluted PH_3 (5%) fed to the main chamber with a typical flow rate of 14 sccm is dissociated by the active electrons. Rf (13.56 MHz) power was supplied to the substrate holder to produce negative self bias which accelerates ions to the substrate. The chamber pressure and substrate temperature were fixed at 1 mTorr and 150 °C or room temperature, respectively. The microwave power was 400 or 500 W. (110)-textured poly-Si films on Corning 7059 glass substrates were mainly used for the doping experiments. The poly-Si was deposited at a low temperature of 300°C by plasma decomposition of a $SiF_4/SiH_4/H_2$ gas mixture[2,3]. (100) and (110) c-Si wafers were also used for comparison. The doped substrates were characterized mainly by sheet resistance measurement and secondary ion mass spectroscopy (SIMS).

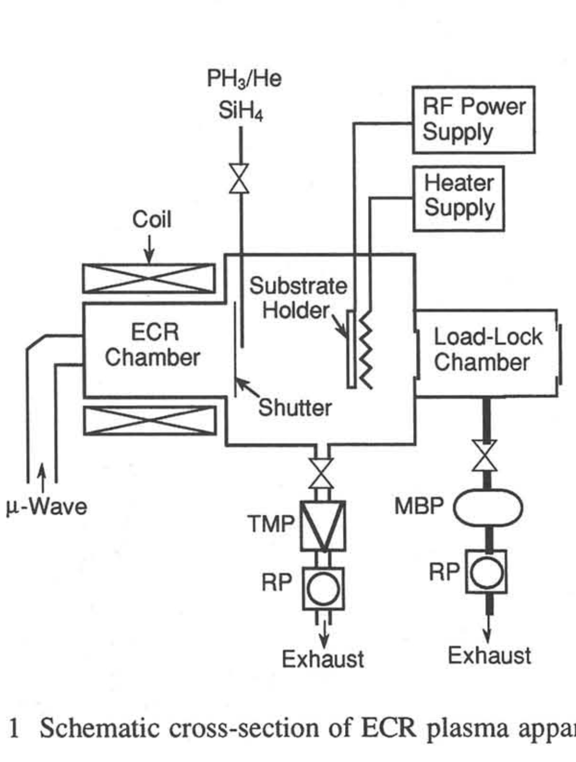

Fig. 1 Schematic cross-section of ECR plasma apparatus.

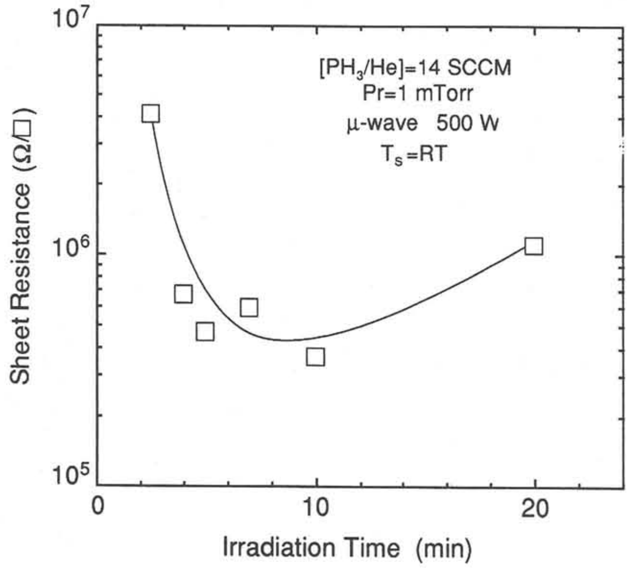

Fig. 2 Irradiation time dependence of sheet resistance.

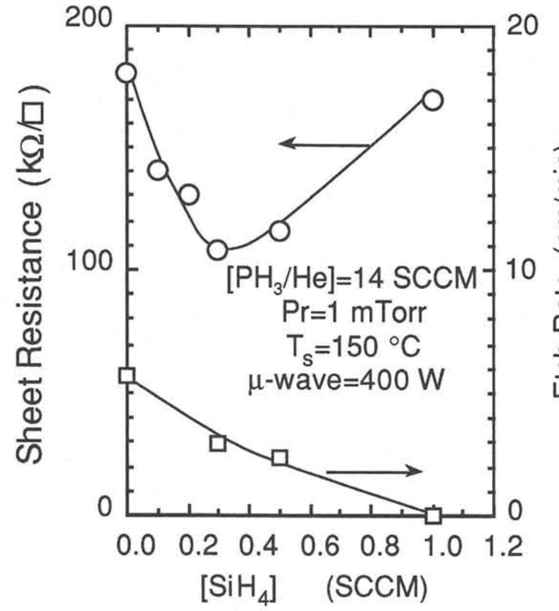

Fig. 3 Sheet resistance and etch rate as a function of SiH_4 flow rate.

3. Results and Discussion

The self bias voltage depended on the flow rate of feed gas, gas pressure and microwave power. Under a fixed condition mentioned above, it linearly decreased to ~-220 V with a maximum rf power of 480 W which we adopted during the experiment. The irradiation time dependence of the sheet resistance R_s of poly-Si is shown in Fig.2. R_s takes a minimum value around 10 min, and increases again with further irradiation. This saturation may be due to the simultaneous etching of the surface, since a large amount of H^+ and He^+ are produced in the ECR plasma; the former can react with the Si surface chemically and the latter physically. Actually, a change of color was observed after irradiation. Then we added a small amount of SiH_4 to PH_3/He to compensate Si atoms.

Figure 3 shows R_s and etch rate as a function of SiH_4 flow rate. As is expected, the etch rate monotonically decreases to ~0 with an increase of SiH_4 to 1 sccm. On the other hand, R_s decreases by a factor of 1.6 around [SiH_4]=0.3 sccm, and increases again for larger flow rates. The increase in R_s at larger flow rates may be due to deposition of amorphous Si and a relative decrease in the P concentration. Reflection high energy electron diffraction (RHEED) experiments showed that the poly-Si surface is amorphized while the (110) c-Si surface remains crystal.

In order to evaluate the P concentration in the substrate, the depth profiles of ^{31}P concentration were measured by SIMS for poly-Si and (110) c-Si irradiated at the optimized condition mentioned above. The depth profiles of ^{1}H concentrations were also measured. The results are shown in Fig.4. It is rather remarkable that P atoms are detected as deep as ~100 nm for poly-Si and deeper for c-Si, despite the low acceleration energy. The deeper detection (~150 nm) of ^{31}P for c-Si can be attributed to the more ordered structure than poly-Si (channeling). As can be seen, the ^{31}P profile for poly-Si consists of two regions, i.e., a shallow region (<10 nm) which has a peak at ~5nm and a deeper region in which ^{31}P decays more gradually. The shallow region may correspond to the amorphized layer, while the deeper region is probably due to diffusion along the grain boundaries. Mizuno et al. pointed out in their ECR doping experiment of boron that dopant atoms reach much deeper than the penetration depth calculated from the diffusion constant, and suggested that this may be due to the transfer of energy from plasma excited electrons in Si to the lattice[1]. Another possibility is that photo-created defects may assist diffusion of dopants, since it is well known that dopant diffusion is assisted by the creation of defects such as Si vacancies or interstitial Si atoms[4]. Figure 4 also shows that the H concentration is much higher than the P concentration particularly for the deeper region of c-Si. This is because of the much larger diffusion constant of H than that of P. For poly-Si, the profile of diffused H atoms are masked by those contained as-grown in the film.

Since R_s depends on the dopant depth and concentration as well as carrier drift mobility, it is necessary to evaluate the resistivity for the electrical characterization of the *doped* layer. For lack of the data of active P concentration and for simplicity, we assumed a simplified model in which the substrate consists of a heavily and homogeneously doped layer with low resistivity ρ and an undoped layer with high ρ. The boundaries of the two layers are set 20 nm for poly-Si and 10 nm for c-Si at which the ^{31}P concentrations decrease to 1/10. The calculated ρ are listed in Table 1 together with R_s values. The ρ values for c-Si indicate fairly low values, in particular, the ρ value of (110) c-Si is near the published value for homogeneously doped c-Si with an impurity level of ~10^{21} cm^{-3} [5]. In contrast, the ρ of poly-Si is lower than what is expected from the difference of drift mobility (~10 cm^2/Vs for the low temperature poly-Si[6]). This can

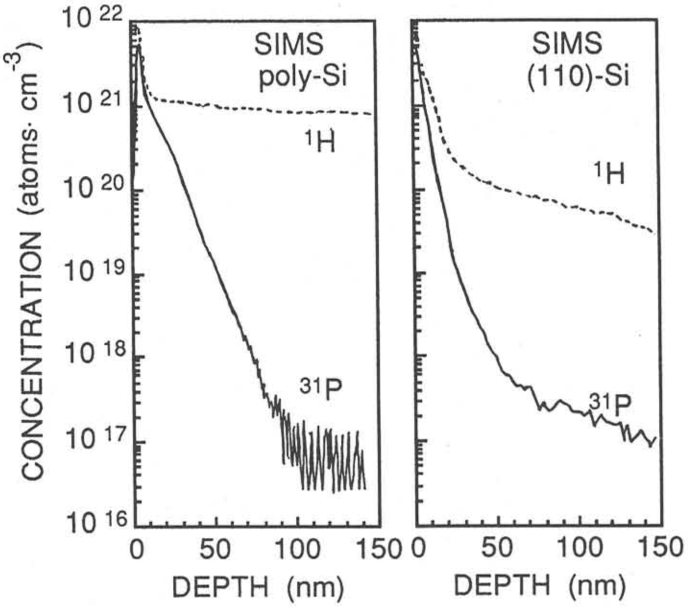

Fig. 4 SIMS profiles of ^{31}P (solid line) and ^{1}H (dotted line) concentrations for poly-Si and (110) c-Si.

be attributed either to the surface roughness (~12 nm) which is comparable to the ^{31}P penetration depth or to the amorphization of the surface mentioned earlier. The reason for the higher R_S of (100) c-Si than that of (110) c-Si is not clear yet, but we suggest that the projected density of Si atoms for the (100) plane is higher than that for the (110) plane, which may restrain the penetration depth of dopant atoms. Annealing at 600 °C reduced R_S by a factor of 2~3. In order to obtain good TFT characteristics, low resistivity contacts are desirable. Development of effective activation at low temperature (<400 °C) is necessary. At this stage we fabricated a test TFT by the ECR doping technique and ascertained on-off characteristics.

Table 1 Sheet resistance and the calculated resistivity of P-doped layer assuming a two-layer model.

Substrate	Sheet Resistance (Ω/□)	Resistivity (Ωcm)
poly-Si	1.0×10^{5}	2×10^{-1}
c-Si <110>	1.7×10^{2}	1.7×10^{-4}
c-Si <100>	1.1×10^{3}	1.1×10^{-3}

4. Summary and Conclusion

We have made fundamental experiments of P doping by an ECR plasma. The P concentration as detected by SIMS was ~5×10^{21} cm^{-3} at the surface which decayed to ~10^{17} cm^{-3} within 50~100 nm depth. The observed etching of the film surface during P doping was restored by adding a small amount of SiH_4, and as a result, R_S decreased by a factor of 1.6. The optimized R_S as irradiated are ~1×10^{5} Ω/□ and 1.7×10^{2} Ω/□ for poly-Si and (110) c-Si, respectively. The ECR doping proved to be a feasible technique for application to the poly-Si driving circuits.

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