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Enhanced Lateral Solid Phase Epitaxial Growth in Phosphorus Doped Amorphous Si Films

Hiroshi YAMAMOTO, Hiroshi ISHIWARA, and Seijiro FURUKAWA Department of Applied Electronics, Tokyo Institute of Technology, Nagatsuda, Midoriku, Yokohama 227, Japan

Characteristics of lateral solid phase epitaxy (L-SPE) in phosphorus implanted amorphous Si films were investigated. It was found that P doping was effective to enhance the L-SPE growth rate and to reduce the random nucleation rate. Owing to these effects, the maximum L-SPE length of about $24\mu m$ was obtained in the film doped with $3x10^{20}$ P atoms/cm³ after 8h-annealing at 600°C, which was fairly longer than that in the undoped films.

1. Introduction

Lateral solid phase epitaxy (L-SPE) of amorphous Si (a-Si) films^{1,2)} is a promising technique to realize silicon on insulator (SOI) structures suitable for 3-dimensional LSI's, since it is a low temperature process. We have shown that a-Si films, which are evaporated on heated (100)Si substrates with SiO₂ patterns and then amorphized by Si⁺ ion implantation, grow laterally onto the SiO₂ patterns. However, the maximum L-SPE length, which is determined by competition between the L-SPE growth rate and the random crystallization (polycrystallization by randomly nucleated grains) time, was limited to 5-6µm along the <010> direction when annealed at 600°C.²) We

Table	1.	Implantation	Conditions
		and particular of the own	

can speculate that electrically active dopants such as phosphorus or boron, which are effective to enhance the vertical SPE rates,³⁾ enhance the polycrystalline grain growth rate as well as the L-SPE rate. Even in these situations, enhancement of the maximum L-SPE length in doped a-Si films is expected if the random nucleation rate is reduced, since the random crystallization time is determined by both the grain growth rate and the nucleation rate. So, in this paper, we investigate the L-SPE characteristics in phosphorus doped a-Si films.

2. Experimental procedure

Si films about 250nm thick were evaporated on thermally-cleaned patterned-SiO₂(~30nm)/(100)Si

Group	Sample	Substrate Temperature	Ion	Energy / Dose (keV) (10 ¹⁵ cm ⁻²)	Concentration; n (cm ⁻³)
1	(a)		28 _{Si} +	160/2.1, 80/0.76, 40/0.38	1.0x10 ²⁰
	(b)			160/6.3, 80/2.3, 40/1.1	3.0x10 ²⁰
2	(c)		31 _P +	180/1.8, 90/0.79, 40/0.37	1.0x10 ²⁰
	(d)	RT		180/5.4, 90/2.4, 40/1.1	3.0x10 ²⁰
3	(e)		31 _P +	*110/1.2, 170/1.9, 80/0.67	1.0x10 ²⁰
	(f)			*110/4.0, 170/5.7, 80/2.0	3.0x10 ²⁰
	(g)			*110/12, 170/19, 80/6.7	1.0x10 ²¹

*through 110nm SiO₂



Fig.2 Optical micrographs for the samples of the groups 1 and 2 annealed at 600°C and etched by Wright etchant. The patterns are directed parallel to the <001> axes.

substrates in an ultra-high vacuum condition at the substrate temperature of ≃500°C. The evaporated films were then amorphized by implantation of Si⁺ or P⁺ ions at room-temperature with the conditions summarized in Table 1. They are classified in three groups. That is, the samples in the group 1 (the samples (a) and (b)) were implanted with Si⁺ ions and the samples in both groups 2 ((c) and (d)) and 3 ((e), (f) and (g)) were implanted with P⁺ ions. The doping concentrations in these samples were nearly constant to the aimed values shown in Table 1 as \overline{n} throughout the evaporated films. The nearly constant concentrations were obtained in the group-2 samples by the multiple-energy implantation. While they were



Fig.1 Implanted phosphorus profiles in the samples of the groups 2 and 3 calcurated by summing the simple Gaussian distributions. The concentration is normalized with the aimed values (\overline{n}) shown in Table 1.

obtained in the group-3 samples by the implantation through thermally oxidized SiO_2 films and by the additional multiple-energy implantation after the removal of the SiO_2 films. The evaporation thickness in the group-3 samples was adjusted to obtain about 250nm thick film after the removal of the SiO_2 . So, the group-2 samples have the lower P concentration in the surface region of about 40nm thickness, as shown in Fig.1. These samples were finally annealed at 600°C in N₂ atmosphere and investigated by Nomarski optical microscopy.

3. Results

In Fig.2, we show optical micrographs of four samples of the groups 1 and 2 which were annealed at 600°C for 2h and etched by the Wright etchant In these micrographs, the patterns were directed nearly parallel to the <001> axes of the Si substrates. We can see from these micrographs that the L-SPE lengths along the <010> direction are about 2µm in the samples (a) and (b) and about 6 and 8µm in the samples (c) and (d), respectively. This result indicates that the L-SPE rate was enhanced by P doping.

We then show in Fig.3 the dependence of the L-SPE lengths in these samples along the <010> direction on annealing time. From this figure, we can see that the L-SPE rates of all four samples decrease during the initial growth stages and then they have saturated values of $\simeq 1.0 \times 10^{-8}$ cm/s for the samples (a) and (b), $\simeq 3.2 \times 10^{-8}$ cm/s for (c), and $\simeq 7.1 \times 10^{-8}$ cm/s for (d), respectively. In this

figure, we can also see that, though the growth rate of poly-grains should be enhanced as the L-SPE growth rate, the random crystallization time, which is shown in the figure as an time when 60-70% of the film was polycrystallized, in the P⁺ implanted films was not enhanced so markedly probably due to the reduction of the random nucleation rate. Owing to these effects, the maximum L-SPE length of about 24µm was obtained in the sample (d), which was fairly longer than that in the Si⁺ implanted films.

4. Discussions

We, then, discuss about the effects of P doping to the L-SPE and random nucleation rates, where we usually use the sample (a), which was implanted with 1×10^{20} Si atoms/cm³, as an undoped reference sample.

4.1. Enhancement of the L-SPE rate by doping

The saturated $\langle 010 \rangle$ L-SPE growth rates at 600°C, which were obtained from Fig.3 and the similar results for the group-3 samples, are plotted in Fig.4 as a function of the doping



Fig.3 L-SPE growth length along the <010> direction of the samples of the groups 1 and 2 as a function of annealing time at 600°C.

concentration. In this figure, we also show the reported dependence of (100) vertical SPE (V-SPE) rate at 475°C which were normalized with the value for an undoped film.³⁾ Note that, the reported enhancement effects by P atoms are similar between the (111) V-SPE rate and the (100) rate.³⁾ From this figure, we can see the following facts. (1) The enhancement effects of P to the saturated <010> L-SPE rate at the doping level of 1-3x10²⁰ $\rm cm^{-3}$ are almost the same between the samples of the groups 2 and 3. (2) About 3- and 7-fold enhancements of the L-SPE rate are obtained at the concentrations of 1 and $3x10^{20}$ cm⁻³, respectively. However, at $1 \times 10^{21} \text{ cm}^{-3}$, the rate is reduced to about 1/3 of the undoped value, probably due to the impurity segregation effect. So. we can say that the maximum enhancement factor by P to the saturated L-SPE growth rate at 600°C is equal to or somewhat higher than 7, which is obtained at the concentration around $3 \times 10^{20} \text{ cm}^{-3}$.

<u>4.2. Reduction of the random</u> <u>nucleation rate by doping</u>

We examined the random nucleation rate in the doped and undoped films annealed at 600° C by counting the numbers of nucleated poly-grains⁴⁾ in the Wright-etched samples. The result is shown in Fig.5 as a function of P concentration. From this figure, we can see the following results. (1) The random nucleation rate in the group-3 samples is about 16 times reduced by P doping at the concen-



<u>Fig.4</u> The saturated $\langle 010 \rangle$ L-SPE growth rate of the samples of the groups 2 and 3 at 600°C as a function of phosphorus concentration.

tration of $1-3x10^{20}$ cm⁻³ and it is about 90 times reduced at $1 \times 10^{21} \text{ cm}^{-3}$. (2) The reduction observed in the group-2 samples is only a factor of about 2 at the concentration of $1 \times 10^{20} \text{ cm}^{-3}$, which is far smaller than that obtained in the group-3 samples with the same concentration. However, the nucleation rate of the group-2 samples become similar or somewhat lower than that of group-3 samples at $3 \times 10^{20} \text{ cm}^{-3}$. (3) The reduction of the nucleation rate obtained in the sample (b), which was implanted with $3x10^{20}$ Si atoms/cm³, is small compared with that obtained in the P doped samples. From these facts, we can say that (1) amorphization of the evaporated polycrystalline films is almost completed by the implantaion of 1×10^{20} Si⁺ ions/cm³ and that the reduction of the random nucleation rate by P⁺ implantation is considered due to their chemical or electrical effect, (2) the nucleation rate is more than 10 times reduced by P doping at the concentration equal to or higher than $1 \times 10^{20} \text{ cm}^{-3}$, (3) the nucleation seems to occur mainly near the surface of the film.

Note that, from the bulk-induced crystallization model⁵⁾, we can see that about 40-fold reduction of the nucleation rate observed in the sample (d) is almost enough to keep the random crystallization time constant against about 7-fold enhancement of the grain growth rate, which is expected from the enhancement observed in the L-SPE rate.



Fig.5 The random nucleation rate of the samples of the groups 1, 2 and 3 at 600°C as a function of implanted atom concentration.

5. Conclusions

We investigated the L-SPE characteristics in P⁺ implanted a-Si films and found that P doping with the atomic concentration around $3 \times 10^{20} \text{cm}^{-3}$ was effective to enhance the L-SPE rate and to reduce the random nucleation rate. That is, comparing with those in the undoped film, (1) the saturated <010> L-SPE growth rate was enhanced as much as about 7 times at the doping concentration around $3 \times 10^{20} \text{ cm}^{-3}$, and (2) the random nucleation rate is more than 10 times reduced at the doping concentration equal to or higher than $1 \times 10^{20} \text{ cm}^{-3}$. Owing to these effects, the maximum L-SPE length of about 24µm was obtained after 8h-annealing at 600°C, which was fairly longer than that in the Si⁺ implanted a-Si films.

At present, it is possible to cover about 50µm wide SiO₂ stripes with epitaxial Si films by the L-SPE growth from the both edges at temperatures not higher than 600°C. It is also possible to grow undoped Si films on the doped ones by low temperature vertical epitaxy such as SPE or molecular beam epitaxy (MBE). From these facts we believe that L-SPE is the most promising technique to fabricate 3-dimensional LSI's with highly stacked structures.

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