Extended Abstracts of the 1997 International Conference on Solid State Devices and Materials, Hamamatsu, 1997, pp. 462–463

Enhancement of Silicon Epitaxy by Increased Phosphorus Concentration in a Low Energy Ion Bombardment Process

H. Kumami[1], W. Shindo[1,2], K. Ino[1,2], and T. Ohmi[1]

[1]Department of Electronic Engineering, Graduate School of Engineering, Tohoku University, Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-77, Japan
Phone: +81-22-224-2649 / Fax: +81-22-224-2549, E-mail: kumami@sse.ecei.tohoku.ac.jp
[2]Laboratory for Electronic Intelligent Systems, Research Institute of Electrical Communication, Tohoku University 2-1-1 Katahira, Aoba-ku, Sendai 980-77, Japan

1. Introduction

VLSI technology has allowed us to integrate incredibly complex functions onto a single chip. For achieving further high performance LSI's, a deep understanding of the mechanism of film growth is necessary. This is because a semiconductor device consists of several layers of thin films, and the film quality of each layer strongly affects the device's performance. Furthermore, lowering process temperature is essential for realizing ultra small dimension devices using metals[1]. Low energy (<100 eV) bombardment processes are quite effective for realizing high quality film growth at very low temperatures. We had previously realized device grade silicon epitaxy at temperatures as low as ~300 °C using low energy, high flux, large mass ion bombardment[2-4]. However, the effect of dopant concentration on low temperature silicon epitaxy had not yet been investigated. The aim of this paper is to report the effect of phosphorus concentration on low temperature silicon epitaxial growth using a low energy ion bombardment process. We found that phosphorus doping dramatically enhanced silicon epitaxial growth at low temperature.

2. Experiment

An rf-dc coupled mode bias sputtering system[2-3] was used to create a low energy ion bombardment process, shown in Fig. 1. A remarkable feature of this system is that important parameters, such as film growth rate, plasma density and ion bombardment energy can be controlled independently. A 100 MHz rf power supply was used to generate a high density plasma under an Ar or Xe gas pressure of 10 mTorr, and the rf power input determines the plasma density, i.e., the ion flux supplied to the wafer. DC power supplies were connected to the target and substrate. The DC voltage applied to the target determines the sputtering rate, i.e., the film growth rate. The DC voltage applied to the substrate determines the magnitude of the kinetic energy of the ions bombarding the film surface. The film growth was performed in an ultra high vacuum chamber whose ultimate pressure was 2×10^{-10} Torr. The sputtering target material was *phosphorus doped* n-type silicon with impurity concentrations of $3\text{-}4\times10^{15}$ cm^{-3} and $3\text{-}4\times10^{19}$ cm^{-3}. The substrate material was n-type (100) silicon.

3. Results and Discussion

A typical reflection electron diffraction (RED) pattern of a single crystal film is shown in Fig. 2. Sharp Kikuchi lines are seen in the diffraction pattern. This indicates that the grown film has perfect crystallinity. The crystallinity of grown silicon films was evaluated by RED analysis in Figs. 3 and 4.

Figure. 3 summarizes the crystallinity of grown films of (a) lightly ($3\text{-}4\times10^{15}$ cm^{-3}) and (b) heavily ($3\text{-}4\times10^{19}$ cm^{-3}) phosphorus doped silicon. The substrate temperature during the deposition was kept at 350 °C. The vertical axis represents the normalized ion flux Ni, defined as the number of bombarding Ar ions per single deposited silicon atom. The horizontal axis represents the Ar ion bombardment energy Ei which is applied to the substrate. The boundary for epitaxial growth was determined on the basis of a number of experimental data. In the lightly doped case ($3\text{-}4\times10^{15}$ cm^{-3}), a single crystal can be achieved only in the shaded region, and the region boundaries are $Ei\times Ni \geq 290$ eV and $Ei \leq 25$ eV. In the heavily doped case ($3\text{-}4\times10^{19}$ cm^{-3}), single crystal growth is realized at lower ion energy (Ei) and ion flux (Ni). The region boundaries are $Ei\times Ni \geq 40$ eV and $Ei \leq 25$ eV. With the lightly doped silicon, no single crystal was achieved using low flux, while there was a single crystal region using high flux. Using high flux is an effective way to create a single crystal. However, even when high flux was used, the single crystal region of heavily doped silicon was much larger than that of lightly doped silicon.

In order to realize epitaxial growth, a sufficient amount of surface activation energy must be provided so that silicon atoms can migrate at the surface and locate themselves at normal lattice sites. Fig. 3 clearly demonstrates the following: (1) $Ei\times Ni$, which represents total energy dose supplied to a single deposited atom, determines the minimum energy threshold for epitaxial growth. Furthermore, the individual ion energy, Ei, has to be lower than ~25 eV to avoid damage caused by excessive ion bombardment. (2) The energy threshold $Ei\times Ni$ is reduced dramatically by increasing phosphorus concentration. The physical mechanism of the second phenomenon has not yet been investigated. However, a similar phenomenon was reported by Csepregi *et al.* They have shown that regrowth rate of amorphous silicon layers produced by ion implantation can be enhanced by adding phosphorus impurities[5]. Although their observation was a bulk reaction and our experiments were focused on a surface interaction, we can be fairly certain that phosphorus dopant can enhance the single crystal growth dramatically.

In order to improve the quality of silicon film of lightly phosphorus doped silicon, following two experiments were performed: heating the substrate to 400 °C and introducing Xe gas. Fig. 4(a) shows deposition temperature dependence of the crystallinity of the lightly phosphorus doped silicon. The single crystal region is enlarged ($Ei\times Ni \geq 30$ eV) by heating the substrate at 400 °C, compared with at 350 °C ($Ei\times Ni \geq 290$ eV). Increasing a process temperature is, however, an undesirable direction. Thus, in order to improve film quality, large mass, large radius ion (Xe^+) bombardment[4] was applied instead of heating the substrate to higher temperatures. Fig. 4(b) shows the crystallinity of the lightly phosphorus doped silicon using Xe ion bombardment. Single crystal growth is realized in very wide range even at 350 °C. The boundaries are $Ei \times Ni \geq 30$ eV and $Ei \leq 30$ eV. The single crystal region of using Xe ion bombardment is much larger than that of using Ar ion bombardment. Therefore, large mass, large radius ion (Xe^+) bombardment is quite effective in promoting epitaxy of lightly doped silicon.

4. Conclusions

We have shown the effect of phosphorus on epitaxial growth in low energy ion bombardment. The conclusions of this study can be summed up as follows: (1) Phosphorus doping enhances silicon epitaxy drastically. (2) Low energy (<25 eV), high flux, large mass (Xe) ion bombardment guides a right direction for enhancing single crystal growth with the lightly doped silicon at low temperature.

Acknowledgments

The majority of this work was carried out in the Superclean Room of the Laboratory for Electronic Intelligent Systems, Research Institute of Electrical Communication, Tohoku University, Japan.

References

1) T. Ohmi: Jpn. J. Appl. Phys. **33**, 6747 (1994)
2) T. Ohmi, T. Ichikawa, H. Iwabuchi, and T. Shibata: J. Appl. Phys. **66**, 4756 (1989)
3) T. Ohmi, K. Hashimoto, M. Morita, and T. Shibata: J. Appl. Phys. **69**, 2062 (1991)
4) W. Shindo, M. Hirayama, and T. Ohmi: Jpn. J. Appl. Phys. **34**, 800 (1995)
5) L. Csepregi, E. F. Kennedy, T. J. Gallagher, J. W. Mayer, and T. W. Sigmon: J. Appl. Phys. **48**, 4234 (1977)

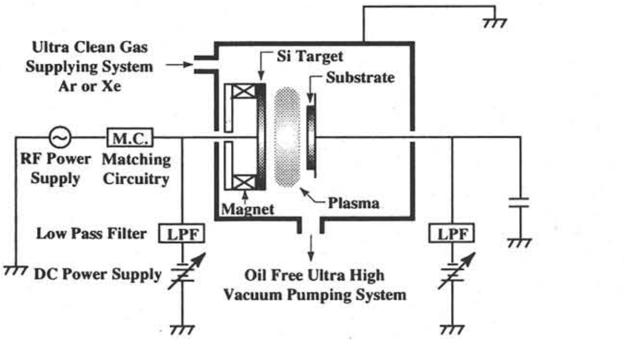

Fig. 1. Schematic of a rf-dc coupled mode bias sputtering system.

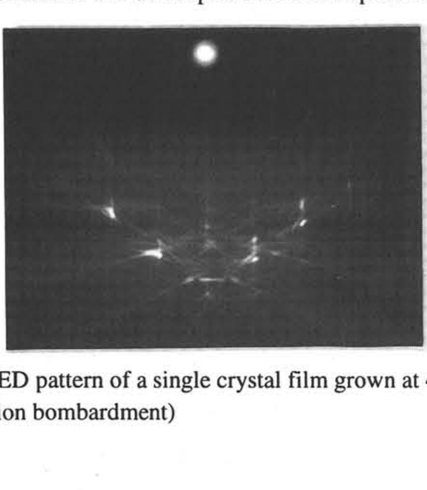

Fig. 2. A RED pattern of a single crystal film grown at 400 °C. (Ei = 7.0 eV, Ar ion bombardment)

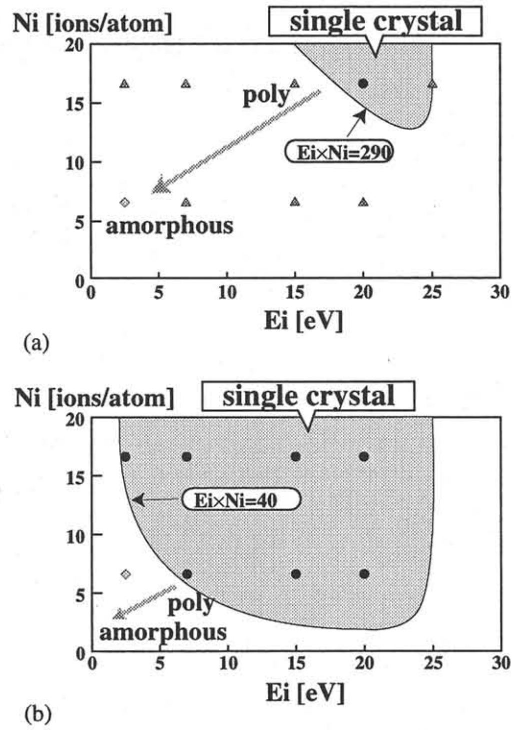

Fig. 3. The dependence of silicon film property on the combination of ion kinetic energy and normalized ion flux. (●) single crystal; (▲) polycrystal; (◆) amorphous. The phosphorus concentrations of the target are (a) 3-4×10^{15} cm^{-3} and (b) 3-4×10^{19} cm^{-3}.

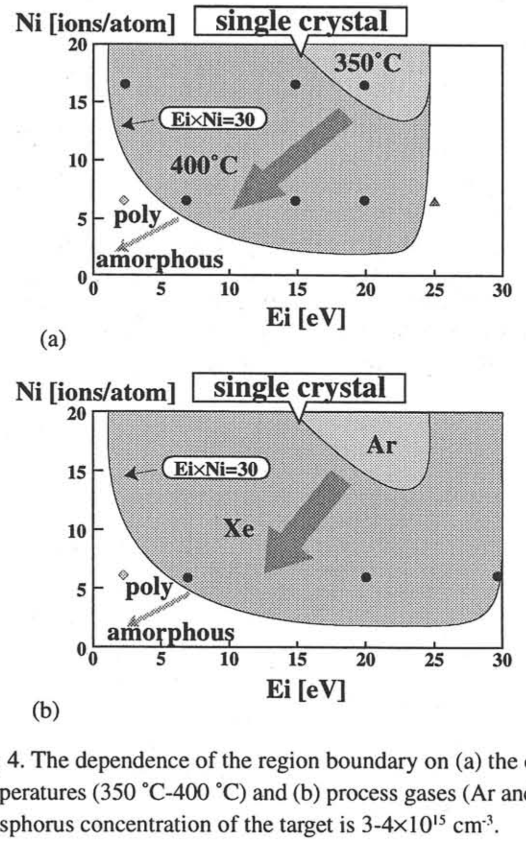

Fig. 4. The dependence of the region boundary on (a) the deposition temperatures (350 °C-400 °C) and (b) process gases (Ar and Xe). The phosphorus concentration of the target is 3-4×10^{15} cm^{-3}.