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Electron and Ion Beam-Stimulated Solid Phase Regrowth of Phosphorus-Implanted Silicon

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Influences of electron (0.1 - 0.8 MeV, 1 - 10 $\mu A/cm^2$) and ion (0.1 - 0.4 MeV, 0.5 - 1.0 $\mu A/cm^2$) irradiation on annealing of ion implanted, damaged Si layers were investigated in the temperature range 250 - 600 C. Two different effects on recrystallization, i.e enhanced solid phase epitaxy by elastic displacements and enhanced annealing of carrier trapping centers by ionization, were clarified.

1. Introduction

Recently it has been shown[1-4] that the temperature required to obtain solid-phase epitaxy (SPE) of amorphous Si layers can be decreased successfully from 550 C to 250 C by the use of ion irradiation during annealing. This finding is of great importance to the development of future low-temperature VLSI processing, especially for Si-on-insulator formation by lateral SPE[5].

Nevertheless, two major questions of both practical and fundamental interest still have to be answered. The first one concerns the crystal quality of layers formed by ion-beam stimulated SPE: is there any degradation of electronic properties due to irradiation? The second question concerns the mechanism of the SPE enhancement, which yet has to be determined. Two possibilities have been proposed: (1) the enhancement of SPE is due to point defects formed by elastic collisions of ions with lattice atoms and (2) the enhancement is related to increased vacancy migration due to ionization of lattice atoms along ion tracks.

In order to address these questions, a comparison was made as a function of irradiation energies between the effects of heavy-particle (ion) irradiation and those of light-particle (electron)[6] irradiation on the recrystallization of ion-implanted Si layers. In addition, the effects of irradiation on annealing of continuous amorphous layers and of isolated-damage layers were compared.

2. Experiments

In the experiments, phosphorus ions with 30 keV energy were implanted into (100) Si surfaces up to a dose of $5x10^{15}$ cm^{-2} (samples A) in order to produce a continuous amorphous layer. For comparison, a low dose of $1x10^{14}$ cm^{-2} was implanted (samples B) in order to produce an isolated-damage layer.

Both kinds of samples were annealed under vacuum conditions (10^{-5} Torr, 250 - 600 C, 20 min) with simultaneous electron irradiation (energy: 0.1 - 0.8 MeV, current density: 1.0 - 10.0 $\mu A/cm^2$) or ion irradiation (energy: 0.1 - 0.4 MeV, current density: 0.5 - 1.0 $\mu A/cm^2$). The sample temperature was monitored by a thermocouple or pyrometer during irradiation. After annealing, crystallinity changes in the implanted layers were analyzed with a channeling/RBS apparatus using 2.0 MeV He^+. The electronic properties and defect states of the recrystallized layers were measured using the four point probe and photoluminescence methods.

3. Ion Beam-Stimulated Recrystallization

Channeling/RBS spectra from samples A annealed at 250 C under $5x10^{15}$ Ne^{+} ions/cm^{2} irradiation (100 keV and 400 keV) are shown in Fig. 1. The spectra from as-implanted and heated-only samples are also shown. The figure shows that the crystallization velocity increases dramatically when ion irradiation is combined with thermal heating. An SPE growth speed of 10^{-9} cm/sec is obtained for samples irradiated at 250 C. In addition , the SPE growth velocity is found to be lower at 400 keV than at 100 keV ion energy. According to the calculations by Johnson and Gibbons[7], the nuclear stopping power decreases when the ion energy is increased from 10 to 400 keV, whereas the electronic stopping power increases. Therefore, it can be concluded that the enhancement of SPE by Ne^{+} irradiation originates mainly from nuclear collisions. In other words, elastic displacements are more important than ionization.

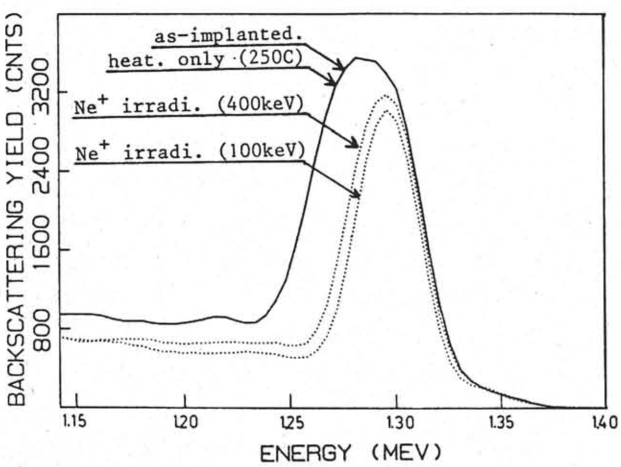

Fig.1 Channeling/RBS spectra of samples A annealed at 250 C, with or without Ne^{+} irradiation.

The sheet resistivity changes of samples A due to ion irradiation-stimulated annealing are shown in Fig. 2. The sheet resistivities decrease when the ion dose is increased at 250 C. When the ion energy is decreased from 400 to 100 keV, the sheet resistivities also decrease. Such electrical characteristics agree well with the crystallinity changes shown in Fig. 1. However, when ion irradiation at 500 C is applied, the sheet resistivities increase due to ion irradiation. This suggests that residual damage, such as complex defects which compensate carriers, is formed during Ne^{+} irradiation.

These results led to the following idea: irradiation should be carried out using particles with a low mass. This is because simple defects generated by light-particle irradiation are expected to be annealed easily. Thus, the following experiments were performed on electron irradiation-stimulated annealing.

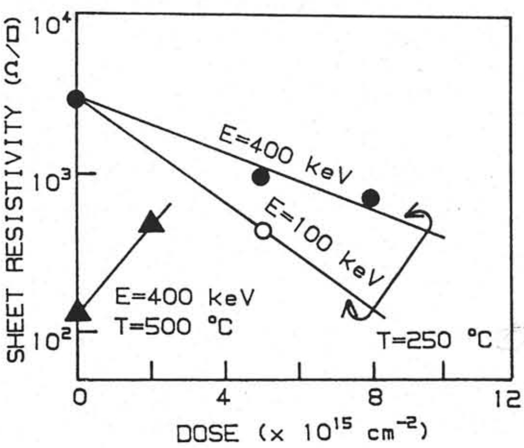

Fig.2 Sheet resistivity changes due to Ne^{+} irradiation at different temperatures and energies.

4. Electron Beam-Stimulated Annealing

The sheet resistivity changes due to annealing with and without electron irradiation (0.8 MeV, $1x10^{17}$ cm^{-2}) are shown in Fig. 3. The utilization of electron irradiation decreases the sheet resistivities for both samples A and B in comparison to those obtained by thermal annealing only. Even after annealing at a relatively high temperature (500 C), the sheet resistivities of electron-irradiated samples were lower than those of samples thermally annealed only. This suggests that crystal degradation by electron irradiation is not so significant. This is a big advantage of electron irradiation compared to ion irradiation.

Channeling/RBS spectra for samples A and B are shown in Fig.4. Spectra of samples A indicate that annealing at 440 C reduced the thickness of the continuous amorphous layer in the direction of the surface region due to SPE growth. When electron irradiation was applied, another small regrowth of 60 A was observed. This enhancement of SPE corresponds to an additional reduction of the sheet resistivities as shown in Fig 3. On the other hand, channeling/RBS spectra for samples B indicate that annealing at 420 C single-crystallized the implanted layer whether electron irradiation was applied or not. Consequently, the enhanced electrical activation for samples B as shown in Fig. 3 can not be explained by the electron irradiation enhancement of SPE.

One possible explanation for the samples B phenomena is that electron irradiation enhances the annealing of carrier trapping centers which are formed after the regrowth of isolated-damage regions[8]. In order to confirm this, photoluminescence measurements were performed on the same samples. The results indicate that the luminescence intensity originating from implantation-induced defects, such as carbon interstitial defects (0.970 eV) and 5-vacancies (1.019 eV) dramatically decrease due to electron irradiation. This supports the idea of the enhanced annealing of complex defects.

In order to distinguish two different mechanisms for electron irradiation-stimulated annealing, i.e elastic displacements and ionization, experiments were carried out using a wide range of electron irradiation energies. This is because displacement effects are expected only for irradiation at energies higher than the threshold electron energy for Si displacement (0.22 MeV)[9].

The enhanced reduction in sheet resistivities due to electron irradiation at 440 C are shown in Fig.5 as a function of electron energy. For samples A, enhanced reduction is obtained only for irradiation at energies higher than the elastic threshold. For samples B, on the other hand, enhanced reduction is found over the entire electron energy range. These results indicate that the displacement effect enhances SPE and the ionization effect enhances the annealing of carrier trapping centers.

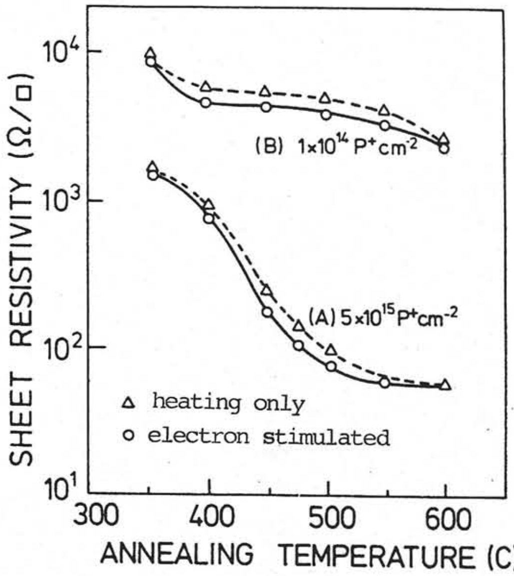

Fig.3 Sheet resistivity changes of samples A and B due to annealing with or without electron irradiation.

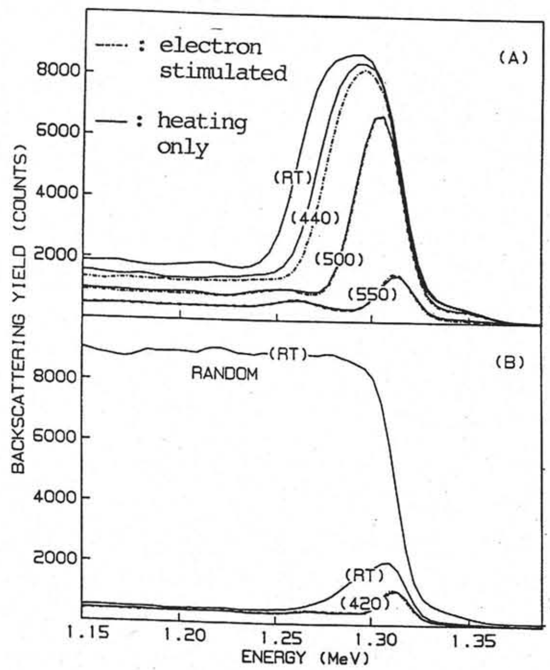

Fig.4 Channeling/RBS spectra of samples A and B, with or without electron irradiation. Substrate temperatures are indicated in brackets.

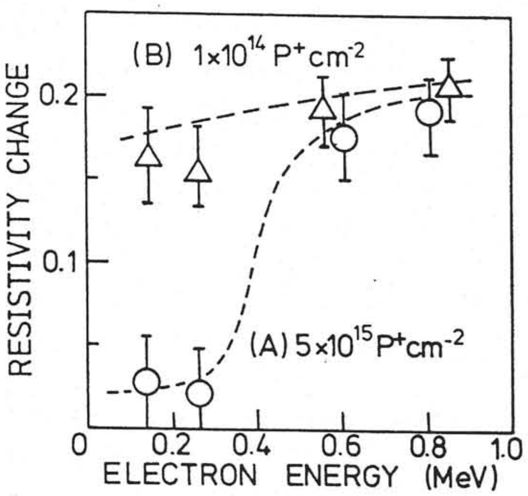

Fig.5 Additional reduction of sheet resistivities due to electron irradiation during thermal annealing normalized to the sheet resistivities obtained by thermal annealing only.

5. Summary

Solid phase regrowth of ion-implanted layers was investigated using electron or ion irradiation to stimulate thermal annealing. Utilization of ion irradiation enhanced SPE velocities drastically due to elastic displacements. However, residual defects due to irradiation degraded electrical properties of regrown layers. Replacing ion irradiation by electron irradiation successfully enhanced SPE velocities without crystal degradation. In addition, ionization was found to enhance the annealing of carrier trapping centers. This phenomenon plays a important role in the electrical activation of implanted atoms in isolated damage regions.

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