Electron irradiation-activated low-temperature annealing of phosphorus-implanted silicon

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High-energy (0.2–0.8 MeV, $\approx 10^{17}$ cm^{-2}) electron irradiation-stimulated solid phase regrowth of phosphorus-implanted silicon layers has been observed in the temperature range 350–600 °C. The influence of electron irradiation on the annealing of an isolated damage layer and of a continuous amorphous layer is compared. An ionization effect is found to enhance annealing of trapping centers in the isolated damage region. In addition, a small enhancement of solid phase epitaxial regrowth of the continuous amorphous layer was found, attributed to an elastic displacement effect.

In recent work[1–4] on ion irradiation-assisted annealing of amorphous silicon layers, an enhancement of solid phase epitaxial (SPE) regrowth with respect to thermally induced regrowth was reported. The recrystallization temperature was successfully decreased from 550 to 250 °C. However, residual damage induced by the irradiation resulted in poor electrical characteristics of the regrown layers.[3,4] For the application of this new annealing method to future VLSI processing, this is a serious problem.

Substitution of ion irradiation by electron irradiation is considered to overcome this problem.[4] This is because simple defects generated by light-mass particle irradiation are known to be annealed easily. In this process, the following two effects can be expected to assist thermal annealing[2,3]: (1) point defects generated by elastic displacements stimulate a solid phase reaction at the amorphous-crystalline interface; (2) ionization effects enhance the atomic rearrangement.

In order to examine these possible mechanisms, the SPE process of ion implanted silicon layers under electron irradiation was investigated. In addition, the influence of the irradiation on the annealing of a continuous amorphous layer and an isolated damage layer was compared.

In the present experiments, p-type (100) silicon wafers (20 Ω cm) were used. Phosphorus ions (30 keV) were implanted up to a dose of 5×10^{15} cm^{-2} (samples A) in order to produce a continuous amorphous layer. In addition, a low dose of 1×10^{14} cm^{-2} was implanted (samples B) in order to produce an isolated damage layer with amorphous clusters in an otherwise crystalline region. Both kinds of samples were annealed under vacuum (10^{-5} Torr, 250–600 °C, 20 min) simultaneously with the electron irradiation. As a sample holder a copper block containing an electric heating element was used. Samples were strongly clamped on the surface to obtain good heat contact. The temperature was probed with two thermocouples fixed near the center portion and the edge of the copper block.

Electron irradiation (0.2–0.8 MeV, 1.0–10.0 μA/cm^2) was performed using the electron Van de Graaff accelerator at the University of Amsterdam. Energies less than 0.6 MeV were obtained by transmitting the electron beam through an Al foil of 1.0–1.5-mm thickness. For 20 min the beam was homogeneously swept over one-half (5×8 mm^2) of the sample surface. Directly after starting the irradiation, the temperature increased due to the several watt electron input. After three minutes irradiation it saturated to about 200 °C. Both thermocouples indicated the same temperature, thus indicating that thermal equilibrium was reached on the copper block. A further temperature increase was obtained using resistive heating.

After annealing under electron irradiation, the crystallinity change in the implanted layers was analyzed in a channeling/RBS apparatus using a 2.0-MeV He$^+$ beam. Electronic properties of the recrystallized layers were measured using the four-point probe method. Errors in the sheet resistivity measurements are 5%.

Figure 1 shows the sheet resistivity change due to isoch-

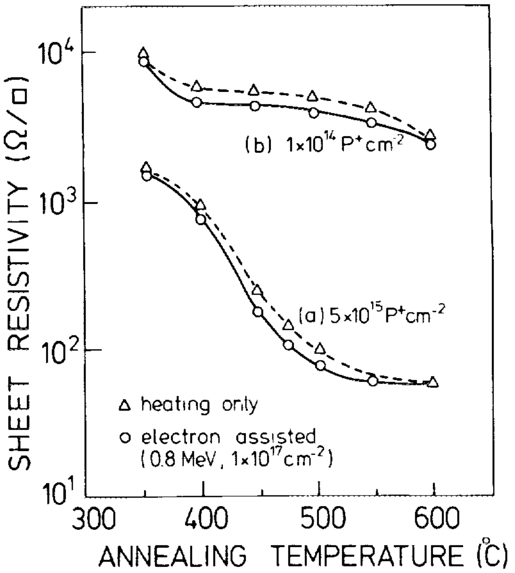

FIG. 1. Sheet resistivity changes due to isochronal annealing (20 min) of phosphorus-implanted silicon [(a) 30 keV, 5×10^{15} cm^{-2}; (b) 1×10^{14} cm^{-2}]. Annealing was done in vacuum with or without electron irradiation (0.8 MeV, 1×10^{17} cm^{-2}). Scattering in the sheet resistivity data is within the circles or triangles.

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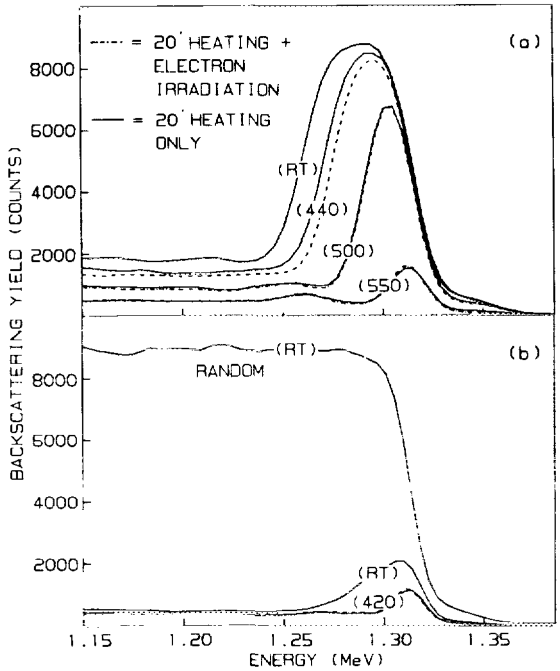

FIG. 2. Channeling/RBS spectra of phosphorus-implanted silicon layers [(a) 30 keV, 5×10^{15} cm^{-2}; (b) 1×10^{14} cm^{-2}] annealed for 20 min with and without electron irradiation (0.8 MeV, 1×10^{17} cm^{-2}) at different temperatures (indicated between brackets in the figure). Spectra of as-implanted, not annealed samples, are also shown (RT).

ronal annealing (350–600 °C, 20 min). The sheet resistivities of samples A decreased strongly with the increase of the annealing temperature [Fig. 1(a)]. On the other hand, the sheet resistivities of samples B decreased mainly in the low-temperature region ($T<420$ °C), a gentler decrease followed for higher temperatures [Fig. 1(b)], as reported previously.[5]

The resistivity change due to combined thermal annealing and electron irradiation (0.8 MeV, 1×10^{17} cm^{-2}) is also shown in this figure. Utilization of electron irradiation decreased the sheet resistivities for both samples A and B in comparison to those obtained by thermal annealing only. In this way, enhanced electrical activation of implanted phosphorous atoms due to the electron irradiation is confirmed for both kinds of samples.

Channeling/RBS spectra for samples A are shown in Fig. 2(a). The spectrum of an as-implanted sample indicates that a continuous amorphous top layer was formed with a thickness of 760 Å. Upon annealing at 440 °C the interface between the high and low yield portions in the spectra was shifted towards the surface region due to SPE regrowth over a distance of 110 Å. When electron irradiation was applied, a small further shift was observed corresponding to additional regrowth of 60 Å. This enhancement of regrowth for samples A corresponds to an additional reduction of the sheet resistivities as shown in Fig. 1. No structural defects were observed in the substrate region after electron irradiation. This is a big advantage of electron irradiation compared to ion irradiation.[3,4]

When the substrate temperature was increased, the effect of electron irradiation became smaller. At a temperature of 500 °C, no SPE enhancement could be detected from RBS spectra.

The channeling/RBS spectra for samples (B) are shown in Fig. 2(b). For as-implanted samples, the silicon peak height of the spectrum was about 20% of the random height. This indicates that single isolated amorphous clusters [cross section 42 (Å)^2] are produced along the ion tracks at this implantation condition.[6] At 420 °C the implanted layer became completely single crystalline whether electron irradiation was applied or not. Consequently, the enhanced electrical activation for samples B at temperatures above 420 °C (Fig. 1) cannot be explained by electron irradiation enhancement of SPE.

One possible explanation for this phenomenon is that electron irradiation enhances the annealing of carrier trapping centers (complex defects), which are known to be formed after the regrowth of amorphous clusters.[6,7]

In order to confirm such a speculation, photoluminescence experiments were done using the same samples.[8] Preliminary results indicated that the luminescence intensity originating from implantation induced defects such as the G center (carbon interstitialcy defects; 0.970 eV) and the W center (five vacancies; 1.019 eV) are decreased due to the electron irradiation. This supports the idea of enhanced annealing of complex defects due to the electron irradiation.

Enhanced annealing of carrier trapping centers by electron irradiation plays a dominant role for the electrical activation of the low-dose implanted samples as well as for the less damaged region beyond the amorphized layer in case of high-dose implantation. Suski and Rzewuski[9] investigated isothermal annealing characteristics of high-dose implanted Si layers (10^{15} P$^+$ cm^{-2}) under electron irradiation. They reported that the annealing time necessary for 10% electrical activation was drastically decreased by the aid of electron irradiation. From our findings we conclude that this result should be explained by the mechanism of enhanced annealing of carrier trapping centers instead of enhanced SPE. This is because the activated carrier concentration of 10% mainly comes from the deep, less damaged region.[6]

It seems difficult to explain our results by beam induced heating effects. Although samples A and B were treated identically the electron enhancement effect is different. Also a color change of the surfaces of the samples due to recrystallization under low-temperature irradiation was limited only to the irradiated portions, i.e., boundaries between electron irradiated and nonirradiated parts remained very sharp. Finally, our results show an enhancement of SPE only below 500 °C. This suggests that the activation energy for SPE regrowth is decreased by electron irradiation.

In order to clarify the mechanisms involved in electron irradiation for both samples A and B, additional experiments were done. As a Si atom displacement effect was suggested to be of importance, experiments were done below and above the threshold electron energy for Si atom displacement (0.22 MeV).[10]

Figure 3 compares the enhanced reduction of sheet resistivity due to electron irradiation at 440 °C for samples A and B as function of electron energy. For samples A, an enhancement was obtained only for irradiation at energies

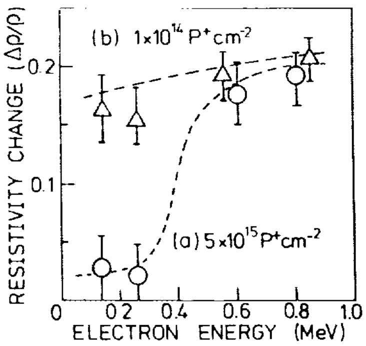

FIG. 3. Sheet resistivity change due to electron irradiation in comparison to thermal annealing only as a function of electron energy. Results for samples A and samples B are compared [curves (a) and (b), respectively].

higher than the elastic threshold [Fig. 3(a)]. This result indicates that defects produced by elastic displacement of silicon atoms due to electron irradiation stimulate SPE growth. On the other hand, for samples B, an enhancement was found for the whole electron energy range [Fig. 3(b)]. This indicates that ionization effects enhance the annealing of carrier trapping centers. One possible explanation for these phenomena is that electron irradiation changes the defect charged state due to an ionization mechanism. This results in a change of the potential energy of defects and enhances the defect mobility.[11,12]

In conclusion, we have demonstrated the useful influence of electron irradiation on the annealing of ion implanted silicon layers. An ionization effect enhances the annealing of carrier trapping centers. This phenomenon plays a dominant role for the electrical activation of implanted atoms in the less damaged region. In addition, a small enhancement of SPE growth in the continuous amorphous layer is observed and must be attributed to an elastic displacement mechanism. After electron activated annealing no structural damage due to electron irradiation is observed.

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