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A-3-1 Low Temperature Annealing Characteristics of Phosphorus-Implanted Silicon

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Annealing behavior of ion implanted silicon in the temperature range around 500°C has not yet been fully investigated. The details of the electrical activation of implanted impurities, the structural change of the crystalline defects in substrates formed during implantation, and especially the inter-relation of both remain unclarified in this temperature range.

On the other hand, from the view point of practical IC technology, the heat treatment in this temperature range would have possible applications such as aluminum metallization process prior to the implantation.

For these reasons we have investigated the annealing process mainly around 500°C of phosphorus implantations both into the uncovered and oxide-covered silicon surfaces, the latter being very important in the device fabrication process.

Silicon wafers of [111] orientation with resistivity of 0.7-1.4 ohm·cm were used for the present experiments. The wafers were tilted 10° with respect to the direction of the ion beam and phosphorus ions with energies of 40-170 keV and with doses of 1.0×10^{14}-$2.1 \times 10^{15}/cm^2$ were implanted. In the case of oxide-covered samples, the dose of phosphorus ions implanted into the silicon substrates, Q_{Si}, was fixed to $3 \times 10^{14}/cm^2$ for all the experiments. All samples were annealed in dry N_2.

Figure 1 shows an example of the change of the sheet resistivity as a function of annealing temperature for through-oxide implanted samples. Sheet resistivity values after low-temperature ($\leq$550°C) annealing decrease as ion energies decrease for the samples with the same oxide thickness. Namely, the doping efficiency after low temperature annealing increases as ion energies decrease.

On the other hand, electron microscope observation of the same samples revealed that the total number of defects increased as ion energies decreased when oxide thickness was kept constant. This result was contrary to that of implantations directly into silicon, where the total number of defects generated during implantation increase with increasing ion energies1). Therefore, our microscope observations indicated that the knock-on effect of phosphorus ions with oxygen atoms in SiO_2 films plays an important role in the defect formation in the silicon substrates2).

In Fig. 2, annealing curves of the sheet resistivity are shown for the samples implanted without oxide (bare silicon) with various energies and a fixed dose ($3 \times 10^{14}/cm^2$). The doping efficiency after low temperature annealing increased with decreasing ion energies. On the other hand, according to the calculation3), it can be shown that the defect density (the vacancy concentration at the peak position of its profile) generated during implantation into bare silicon increases with decreasing ion energies when the dose of ions is fixed.

Therefore, our experimental results combined with calculated results3) could lead to the conclusion that the increase of the doping efficiency after low temperature annealing was caused by the increase of the defect density and not by the increase of the total number of defects.

However, damages in the substrate crystal may not be fully recovered by such a low temperature annealing and this leads to the question that when the defect density becomes very high, whether the doping efficiency could reach to such high values shown in Figs. 1 and 2. So, the tendency of the preceeding experiments, the increase of the doping efficiency with the increase of the defect density, should have some limited range of the existence.

To clarify such a relation between the doping efficiency and the defect density, we have measured the doping efficiency at 480°C annealing as a function of ion dose at a 50 keV energy. Figure 3 shows a typical example of the result. Under our implantation conditions, the doping efficiency increased rapidly with doses up to the dose of $4 \times 10^{14}/\text{cm}^2$ and then decreased sharply with increasing ion dose. The corresponding dose for the peak position in the curve agrees with the critical dose of amorphous layer formation[4]. At the doses below the critical dose (region A), the isolated damage regions including the complexes of point defects will be formed in as-implanted layers, while at the doses above the critical value (region B), a continuous amorphous layer formation will occur.

In the region A, some kinds of defects formed in damage regions will be decomposed by annealing at this temperature and at the same time implanted phosphorus ions lying within the damage regions will be placed into substitutional lattice sites. Accordingly, the increase of the amount of defects contributes to the release of vacancies and results in increasing the doping efficiency. In the region B, however, where an amorphous layer is already formed, the recrystallization of a continuous amorphous layer may not occur at this annealing temperature[4]. To activate electrically the implanted phosphorus incorporated in the amorphous layers, therefore, a higher temperature annealing will be necessary and epitaxial recrystallization of the damaged layer must be required.

References

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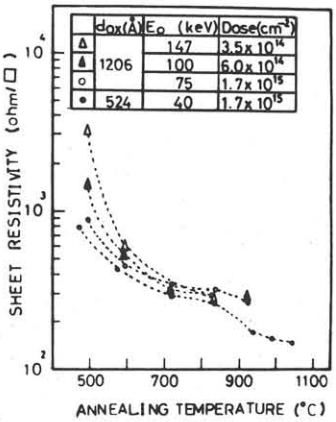

Fig. 1 The sheet resistivity as a function of annealing temperature for different energies (through-oxide implantation).

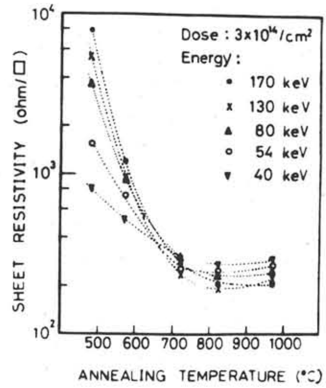

Fig. 2 The sheet resistivity as a function of annealing temperature for different energies (bare silicon implantation).

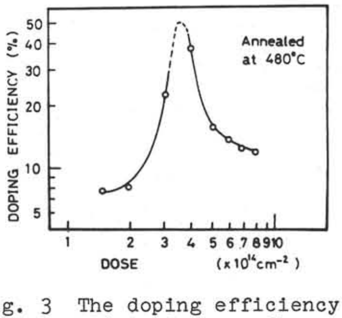

Fig. 3 The doping efficiency as a function of dose after 480°C annealing.