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Activation and deactivation of phosphorus in silicon-on-insulator substrates

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ABSTRACT

Phosphorus that had been implanted into silicon-on-insulator (SOI) substrates was activated using different annealing techniques to investigate phosphorus deactivation at low temperatures. A combination of amorphization and excimer laser annealing (ELA) greatly enhanced phosphorus activation. However, heavy doping with phosphorus reduced the thickness of the amorphous layer. Furnace annealing at 350 °C following ELA induced significant deactivation and the deactivation behavior was similar to that following rapid thermal annealing (RTA). The temperature-dependence of phosphorus deactivation in samples that were implanted with a dose of 5×10^{16} cm^{-2} showed a transition at 400 °C. The deactivation behavior was more sensitive to temperature below 400 °C than above it. Samples with an implantation dose of 5×10^{15} cm^{-2} exhibited only a weak temperature-dependence of deactivation at temperatures above 400 °C, implying that the transition of temperature-dependence is caused by the change of the deactivation mechanism with the phosphorus activation level.

1. Introduction

Thin body structures have been fabricated to suppress short channel effects in advanced metal-oxide-semiconductor (MOS) transistors. However, such structures also reduce the cross-sectional area of the source/drain regions, resulting in a high series resistance during device operation, affecting the operating speed of the integrated circuits. Therefore, contact resistance needs to be scaled with the dimensions of the device. The active dopant concentration near the surface region critically affects the contact resistance. Increasing the concentration of space charges reduces the thickness of the depletion region and improves the efficiency of carrier tunneling through the energy barrier at the contact. Annealing at high temperatures increases the solid solubility of the dopants. However, dopants deactivation may occur during subsequent processes at low temperatures. When three-dimensional circuits are formed using stacked devices [1], more low-temperature processes for deposition of interconnect layers are required. Such processes enhance dopant deactivation in the underlying active devices. Deactivation behaviors at low temperatures must be understood. Among n-type dopants, phosphorous is frequently used for contact implantation. Phosphorus and carbon can be doped together into source and drain regions, which then undergo laser annealing to improve the driving current of the device [2]. Nobili et al. [3] utilized laser annealing to produce supersaturated phosphorus and observed deactivation at low temperatures. Takamura et al. reported interstitial generation by the deactivation of laser-annealed phosphorus [4]. Suzuki et al. demonstrated the evolution of resistivity during deactivation [5]. However, the behavior of deactivation at low temperatures is still unclear. In this work, silicon-on-insulator (SOI) substrates were utilized to obtain phosphorus profiles with better uniformity than those in bulk silicon wafers. Excimer laser annealing (ELA) and amorphization were performed to improve phosphorus activation to enable the decay behavior of active phosphorus atoms at low temperatures to be identified.

2. Experimental

In this work, ⟨100⟩-orientated p-type SOI wafers that had been prepared by separation-by-implantation-of-oxygen (SIMOX) were used. The thicknesses of the active silicon layer and the buried oxide were around 200 nm and 400 nm, respectively. A screen oxide with a thickness of 15 nm was grown using dry oxidation. Ion implantation was then performed to prepare four groups of samples with different total doses of phosphorus in the silicon layer. The group of samples with a total dose of 5×10^{16} cm^{-2} was obtained by the combination of three implants at 30, 50 and

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70 keV with doses of 1.5×10^{16}, 2×10^{16} and 1.5×10^{16} cm^{-2}, respectively. Implantation at a dose of 5×10^{15} cm^{-2} was performed twice at 50 and 70 keV respectively to prepare the group of samples with a total dose of 1×10^{16} cm^{-2}. Other two groups of samples with phosphorus doses of 1.5×10^{15} and 5×10^{15} cm^{-2} were prepared by implantation at 50 keV. Furnace annealing (FA) was carried out at 1100 °C for 2 h to remove damage that was caused by implantation and to improve the uniformity of the distribution of the phosphorus. The low temperature ramp rate during FA may have caused some deactivation. Consequently, rapid thermal annealing (RTA) was performed at 1100 °C for 1 min to reactivate the phosphorus. Following RTA, some samples underwent additional ELA using a KrF excimer laser with a wave length of 248 nm. The pulse duration of the laser beam was about 20 ns. The energy density used for ELA ranged from 0.4 to 0.6 J/cm^{-2}. Amorphization had been performed at −15 °C using silicon implantation at 80 keV with a dose of 1×10^{15} cm^{-2} before ELA to improve the activation level of the phosphorus. The samples were mounted on a chilled stage and left for 30 min to cooling. Silicon implantation was then performed with a beam current of about 30 μA. The thickness of the amorphous layer was monitored using cross-sectional transmission electron microscopy (XTEM). The chemical concentration of phosphorus was analyzed by secondary ion mass spectrometry (SIMS) at Evans Analytical Group using Cs$^+$ as the primary ions. An electron beam was used for charge compensation. The deactivation of phosphorus was induced during FA at low temperatures. The active dose of phosphorus was analyzed by Hall measurement using the Van der Pauw method. The Hall scattering factor was assumed to be unity. Samples were cycled between FA and Hall measurement.

3. Results and discussion

Fig. 1 shows phosphorus activation after RTA at 1100 °C in samples with different total doses in the active silicon layer. The amount of active phosphorus is proportional to the phosphorus implantation dose below 1×10^{16} cm^{-2}. The phosphorus profiles that were measured by SIMS are almost uniform in the silicon region for the SOI that received phosphorus at doses lower than 1×10^{16} cm^{-2}. The SIMS concentration of phosphorus in samples with a total dose of 1×10^{16} cm^{-2} is around 5×10^{20} cm^{-3}. Notably, the measured active dose is slightly less than the total implantation dose, possibly owing to the segregation of phosphorus at the interfaces between silicon and silicon oxide [6]. The uniformity of phosphorus in silicon in samples with a total implantation dose of 5×10^{16} cm^{-2} became worse as the phosphorus concentration increased over 2×10^{21} cm^{-3}. This can be attributed to complex formation upon interactions between phosphorus atoms [7], which reduces the amount of mobile phosphorus atoms. The formation of phosphorus complexes also affected the activation level. Consequently, when the total dose of phosphorus increased to 5×10^{16} cm^{-2}, a minor increase of the activation level was observed. Fig. 1 also shows the decrease in sheet resistance as the activation level increases in samples that received phosphorus doses of less than 1×10^{16} cm^{-2}. However, the sheet resistance was higher when the total dose of implanted phosphorus was 5×10^{16} cm^{-2} owing to the formation of phosphorus complexes and carrier scattering with ionized phosphorus.

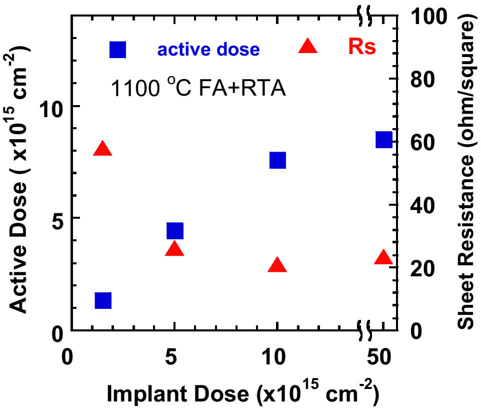

Fig. 1. Active dose and sheet resistance in samples with different phosphorus implantation doses after FA and RTA at 1100 °C.

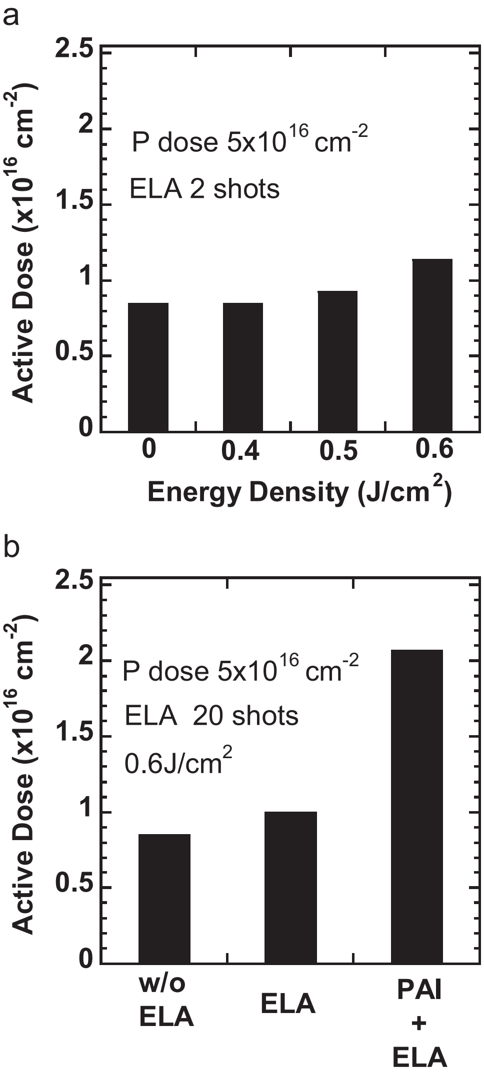

Fig. 2. Improvement of phosphorus activation for samples implanted with a dose of 5×10^{16} cm^{-2} under ELA for (a) 2 shots at different energy densities and (b) 20 shots at 0.6 J/cm^{-2}.

Fig. 2(a) presents phosphorus activation after ELA for two shots. Before ELA, the samples had been annealed at 1100 °C following phosphorus implantation with a total dose of 5×10^{16} cm^{-2}. A minor improvement in activation was observed at a fluence of 0.5 J/cm^{-2}. The phosphorus activation was increased by over 40% when ELA was performed at 0.6 J/cm^{-2}. Fig. 2(b) displays a similar activation with ELA at 0.6 J/cm^{-2} for 20 shots. The variation in the active phosphorus dose was around 20% between samples with and without stripping surface oxide before ELA, implying that the screen oxide may have absorbed some laser energy. Some phosphorus may diffuse through oxide during ELA. The dose loss of phosphorus during ELA was kept within 8% when samples were