Formation of buried oxide in silicon using separation by plasma implantation of oxygen

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Plasma immersion ion implantation (PIII) is used to fabricate buried oxide layers in silicon. This “separation by plasma implantation of oxygen” (SPIMOX) technique can achieve a nominal oxygen atom dose of $2 \times 10^{17}$ cm$^{-2}$ in implantation time of about 3 min. SPIMOX is thus presented as a practical high-throughput process for manufacturing silicon-on-insulator. In the SPIMOX samples prepared, three distinct modes of buried oxide microstructure formation are identified and related to the as-implanted oxygen profiles. A first-order model based on oxygen transport and oxide precipitation explains the formation mechanisms of these three types of SPIMOX layers. © 1995 American Institute of Physics.

Silicon on insulator (SOI) structures have many attractive applications in integrated circuit technology. SOI substrates are usually fabricated by separation by implantation of oxygen (SIMOX) or bond and etch-back (BESOI) techniques. The high cost of manufacturing the SOI wafer, however, prevents it from being widely accepted for very large scale integrated (VLSI) production. In case of SIMOX, the high cost of manufacturing is due to the long time required to achieve the necessary dose in the oxygen implantation. One industrial solution is to increase the current of the implant, thus increasing the dose rate and reducing the implantation time. A lower-energy and lower-dose SIMOX process [thin SIMOX (Ref. 4)] has been reported recently, which improves the SIMOX process time by reducing the necessary dose by forming a thin SIMOX layer. This process shows great promise for low-power electronics because of its compatibility with fully depleted field effect transistor. In this letter, an even more efficient technique to form thin SIMOX using plasma immersion ion implantation (PIII) is presented. This extremely high throughput SOI formation process is named as “separation by plasma implantation of oxygen” (SPIMOX).

The use of PIII for integrated circuit technology in various doping applications such as ultrashallow junction formation and microscopic conformal doping of trenches have been reported in the literature. The PIII reactor has a simple mechanical design and is compatible with cluster-tool integrated circuit (IC) manufacturing. Another attractive feature of PIII for the SPIMOX process is the high dose rate achievable. During plasma implantation, a negative bias voltage is applied to the wafer holder which is immersed in an oxygen plasma. While the bias is present, oxygen ions present in the plasma are accelerated across the plasma sheath layer and implanted simultaneously over the entire wafer. With this process, the implantation time is independent of the wafer size as the implantation current density is independent of the area of implant and the whole wafer gets implanted at the same time.

The PIII principle is illustrated in Fig. 1. The oxygen plasma for SPIMOX was created in an electron cyclotron resonance (ECR) source chamber using a 2.45 GHz microwave excitation. A negative bias of 50 kV is applied to the 4 in. Si wafer. During implantation, the wafer was kept above 600 °C and immersed in the oxygen plasma inside the process chamber. A nominal oxygen atom dose of $2 \times 10^{17}$ cm$^{-2}$ was achieved in about 3 min of implantation. The implanted wafer was capped with 200 nm of sputtered Si$_3$N$_4$ and annealed in a nitrogen gas ambient between 1100 to 1250 °C for 2 h to obtain buried oxides. Cross-sectional transmission electron microscopy (XTEM) and Rutherford backscattering spectrometry (RBS) were used to characterize the samples.

Cross-sectional TEM micrographs in Fig. 2 show the morphologies of the three different modes of buried oxide

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FIG. 1. Schematic of plasma immersion ion implantation (PIII) used in the SPIMOX process. The implantation energy is provided by the voltage drop across the plasma sheath.

structure before and after high-temperature annealing. Since a maximum voltage of 50 kV was used, the SPIMOX process belongs to the thin SIMOX category in which the continuous buried oxide layers are not achieved during the implantation [Figs. 2(a), 2(c), and 2(e)] but formed in the postimplantation annealing stage [Figs. 2(d) and 2(f)]. For a low oxygen dose ($<1 \times 10^{17}$ atoms/cm$^2$), the isolated silicon dioxide precipitates do not grow large enough to form a continuous oxide layer [Figs. 2(a) and 2(b)]. However, at high oxygen dose ($>3 \times 10^{17}$ atoms/cm$^2$), a single buried oxide layer is observed [Figs. 2(c) and 2(d)]. When comparable O$^+$ and O$_2^+$ concentrations are present in the plasma, a double oxide layer (Si/oxide/Si/oxide/Si) structure is produced by a single implantation step [Figs. 2(e) and 2(f)].

The different modes of buried oxide formation are explained by the oxygen depth profile extracted from RBS measurement of the as-implanted samples [Figs. 3(a), 3(c), and 3(e)]. Silicon substrate has been assumed to be pure silicon when extracting these data, which is reasonable due to the light mass of oxygen and the similar stopping power of Si and SiO$_2$. Since PIII does not utilize mass separation, both O$^+$ and O$_2^+$ ions are implanted causing the double peak seen in the implanted oxygen profile. Broader oxygen profiles lead to spreading in depth of the oxide precipitates [Fig. 2(b)] and nonplanar Si top layer [Figs. 2(d) and 2(f)]. Higher annealing temperature (e.g., 1300 °C) and longer annealing

![FIG. 2](image-url) Cross-section TEM micrographs of microstructures of as-implanted samples (a), (c), and (e) and of postannealed samples (b), (d), and (f), showing effect of the implanted oxygen profile and the dose before and after thermal annealing. The total oxygen dose for modes I, II, and III are 1, 3, and $1.8 \times 10^{17}$ O atoms cm$^{-2}$, respectively.

![FIG. 3](image-url) Oxygen profiles (a), (c), and (e) extracted from RBS spectra of the as-implanted samples that corresponding to the three modes of buried oxide microstructures after annealing. In (b), (d), and (f), the oxygen atom diffusion fluxes during annealing are indicated by arrows.
time (e.g., 3 h) can improve the flatness of these Si/SiO$_2$ interfaces. Although pinholes and misoriented silicon particles from recrystallization (indicated by the moiré fringes) can be seen in the silicon layer(s) in Figs. 2(d) and 2(f), crystallinity with the orientation of original target silicon matrix has been kept in most area of the top silicon film. The quality of the top silicon layer can be improved when using higher implantation voltage and higher annealing temperature. Figures 3(b), 3(d), and 3(f) show schematics of the three morphologies formed after annealing. The arrows indicate the oxygen flux during annealing. In mode I, due to the low dose used, only a few precipitates can grow before depleting all of the implanted oxygen. These precipitates are not dense enough to coalesce and form the continuous oxide layer. The mode II growth shows a dominant, single-peak oxygen profile indicating that this mode occurs when a higher concentration of O$_2^+$ ions is present in the plasma. Although a long O atom trail is present in the as-implanted oxygen profile due to the coexistence of O$^+$ in the plasma, the Oswald ripening mechanism depletes the oxygen from this tail for the growth of single buried oxide layer during annealing. Diffusion toward the single oxide layer is the dominant component of the O atoms in this case. In mode III, the O$^+$ and O$_2^+$ concentrations are approximately 2:1 in the plasma, leading to two peaks of similar height in the as-implanted profile [Fig. 3(e)]. This results in a double oxide layer formation upon high-temperature annealing.

In summary, the feasibility of forming buried oxide structures in silicon using SPIMOX is demonstrated. The implant dose rate for this process is very high with a nominal dose of $2 \times 10^{17}$ cm$^{-2}$ achieved in 3 min. The buried oxide morphology is found to be dependent on the implantation profile. A single, dominate oxygen peak is found to be necessary to form a continuous, single-layer, buried-oxide thin SIMOX.

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5 F. Namavar, E. Cortesi, B. Buchanan, and P. Sioshansi, 1989 IEEE SOS/ SOI Technology Conference, p. 117.