APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 5 4 FEBRUARY 2002

Dose-energy match for the formation of high-integrity buried oxide layers in low-dose separation-by-implantation-of-oxygen materials

Meng Chen,[a)] Xiang Wang, Jing Chen, Xianghua Liu, Yeming Dong, Yuehui Yu, and Xi Wang
Ion Beam Laboratory, Shanghai Institute of Metallurgy, Chinese Academy of Sciences, Shanghai 200050, China

(Received 5 June 2001; accepted for publication 19 November 2001)

High-quality low-dose separation-by-implantation-of-oxygen (SIMOX) silicon-on-insulator (SOI) wafers have been fabricated from a series of good matches of dose-energy combinations. The results reveal that a wafer fabricated at an optimum dose-energy match has a superior SOI layer with a low threading dislocation density, a high-integrity buried oxide (BOX) layer with a minimal detectable silicon island density and a low pinhole density. This work introduces an approach to flexibly control the thickness of both SOI and BOX layers, allowing the fabrication of ultrathin SIMOX wafers with ultrathin SOI and BOX layers, and improving the throughput capacity by selecting good dose-energy matches. A possible mechanism is discussed. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1447005]

In recent years, there has been a growing interest in low-dose (dose$<1.0\times10^{18}$ cm^{-2}) separation-by-implantation-of-oxygen (SIMOX)[1–3] silicon-on-insulator (SOI) materials because thin buried oxide (BOX) SIMOX has been shown to improve wafer quality in all aspects as compared with a full dose SIMOX wafer, such as drastically reduced threading dislocation density, metallic contamination, uniformity of SOI and BOX layers, due to the lowered oxygen dose by reducing the implantation time, which simultaneously makes it possible to cut down the production cost. The other advantages include improved device performance and thermal conductivity. Furthermore, thinner Si top layers are desirable for fully depleted devices, and thinner BOX layers are more radiation hard because they trap less positive charge.[4] Development of high-quality low-dose SIMOX material is a key element in the high volume manufacturability and long-term economic viability of SIMOX material in mainstream integrated circuit applications.[5] However, the high density of pinholes (holes through the BOX, connecting the superficial silicon and bulk silicon) and Si islands in low-dose SIMOX materials have been reported to be responsible for increased electrical leakage current through the BOX, or in extreme cases, its dielectric breakdown, which consequently effects the achievement of a high yield for integrated circuits on SOI materials.[6] Many efforts have been made over the past years for the fabrication of high-quality low-dose SIMOX wafers,[1–3,7,8] such as ITOX (Ref. 9) and Advantox (Ref. 10) approaches, but most focus on how to optimize the dose at a fixed energy or introduce a special annealing procedure.[9,11] In this letter, an effort was made to directly fabricate high-quality low-dose SIMOX wafers by optimizing the dose-energy match. The relationship between the quality of low-dose SIMOX wafers and the dose-energy match was investigated.

Oxygen ions ($^{16}O^+$) were implanted into 100 mm *p*-type (100) Czochralski silicon wafers with doses of $2.5–5.5\times10^{17}$ cm^{-2} at an angle of incidence approximately 7° to the surface, at acceleration energies of 70–160 keV. The implantation parameters were summarized in Table I. The wafer temperature during the implantation was maintained at 680 °C, both to effectively eliminate defects generated in the superficial Si layers and to prevent Si sublimation at the surface.[12] All samples were subsequently annealed in an $Ar+O_2$ ($<3\%$) ambient over 1300 °C for 5 h. The structure evolution of the thin-film specimen was examined by cross sectional transmission electron microscope (XTEM) on a JEM-4000EX. A modified enhanced Secco etching method was applied to estimate the threading dislocation density in the SOI layer, where the pits created by modified Secco etching were observed using an optical microscope. Pinhole defects in the BOX layer were counted visually after the $CuSO_4$ electrolytic plating technique was performed.

Figure 1 shows the dependence of microstructure evolution on energy for samples implanted with the dose of 4.5 $\times10^{17}$ cm^{-2} (Group 2). It is seen that the sample at 130 keV (S5) has a minimal detectable silicon island density in the

TABLE I. Implantation parameters.

Sample No.		Energy (keV)	Dose ($\times10^{17}$ cm^{-2})
	S1	160	
Group 1	S2	130	5.5
	S3	100	
	S4	160	
Group 2	S5	130	4.5
	S6	100	
	S7	160	
Group 3	S8	130	
	S9	100	3.5
	S10	70	
Group 4	S11	100	2.5
	S12	70	

[a)]Author to whom correspondence should be addressed; electronic mail: mchen@itsvr.sim.ac.cn

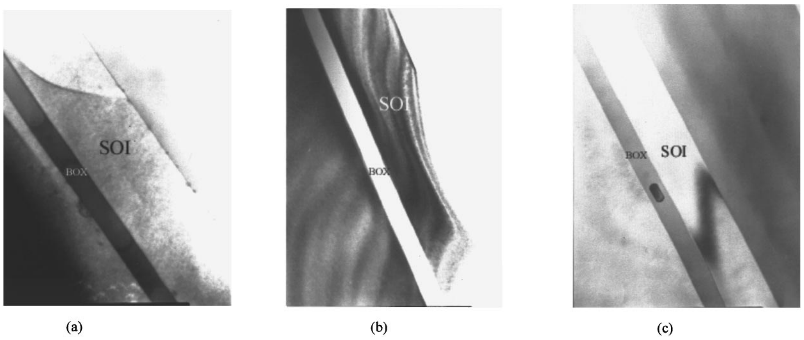

FIG. 1. Dependence of microstructure evolution on the energy for samples implanted with the oxygen dose of 4.5×10^{17} cm^{-2} at the energies of (a) 160 keV, (b) 130 keV, and (c) 100 keV.

BOX layer, while samples of 160 keV (S4) and 100 keV (S6) have densities of about 9.40×10^{7} cm^{-2} and 1.59×10^{7} cm^{-2}, respectively. The dependence of microstructure evolution on the energy was validated by Groups 1, 3, and 4, where samples were fabricated at the doses of 5.5×10^{17} cm^{-2}, 3.5×10^{17} cm^{-2}, and 2.5×10^{17} cm^{-2}, respectively. The results indicate that high-integrity BOX layers had been formed in the samples of S1, S9, and S12, which were implanted to the dose of 5.5×10^{17} cm^{-2} at 160 keV, 3.5×10^{17} cm^{-2} at 100 keV, and 2.5×10^{17} cm^{-2} at 70 keV. While in S2, S3, S7, S8, S10, and S11, which were implanted outside of the appropriate matches of dose and energy combination, numerous silicon islands have been observed. Figure 2 gives the XTEM pictures of S1, S9, and S12.

The XTEM micrographs did not reveal the presence of threading dislocation in all samples, indicative of a defect density below the detection limit of the XTEM. Chemical analysis of defects by diluted Secco[13] was introduced to characterize the occurrence of defects in these materials. Samples implanted with the dose of 5.5×10^{17} cm^{-2} at 160 keV, 130 keV, and 100 keV have threading dislocation densities of 6.52×10^{2} cm^{-2}, 1.01×10^{4} cm^{-2}, and 7.89×10^{4} cm^{-2}, respectively. Samples implanted with the dose of 4.5×10^{17} cm^{-2} at 160 keV, 130 keV, and 100 keV have the values of 5.8×10^{5} cm^{-2}, 6.52×10^{2} cm^{-2}, and 4.52×10^{3} cm^{-2}, respectively. Further studies on Groups 3 and 4 revealed that the S9 and S12 have minimal threading dislocation densities compared to the others. This shows that threading dislocation density in the SOI layer exhibits a strong dependence on the dose-energy match. The threading dislocation densities in samples S1, S5, S9, and S12 are lower than 10^{4} cm^{-2}, which is below that found for the conventional full dose commercial SIMOX materials,[1] indicative of an improvement in the quality of SOI layer.

$CuSO_4$ electrolytic plating technique was applied to characterize the pinhole density in the BOX layer. It was revealed that the samples S1, S5, S9, and S12 have pinhole densities of about 2–4 cm^{-2}, much lower than the other samples, suggesting a strong relationship between integrity of the BOX layer and the dose-energy match. The lowest pinhole density in our samples, however, is still higher than that of commercial SIMOX wafers, which is mostly attributed to the other experimental conditions such as cleaning and annealing procedures.

Figure 3 plots a series of good matches of dose-energy combination for the formation of high-quality low-dose SI MOX materials. In Fig. 3, the solid circles come from present experiments, the open circle from Nakashima,[1] the open diamonds from Jiao[3] and Anc,[13] the open down triangle from Auberton-Herve[7] and the solid square from Ogura.[11] The solid line is plotted as a guide. It is seen around the solid line, that high-quality SIMOX wafers have been fabricated with fixed cleaning and annealing procedures from a series of good dose-energy matches. Furthermore, the higher the oxygen dose, the higher the implanted energy required for the formation of a high-integrity BOX layers with minimal detectable silicon islands. This also implies that the thickness of both SOI and BOX layers would be synchronously shifted, i.e., thinner SOI layers corresponding thinner BOX layers, for the formation of high-quality low-dose SIMOX materials with low detectable silicon islands in BOX layers. Otherwise, a special annealing procedure should be introduced to form a high-integrity BOX layer for those implantation parameters far away from the solid line, such as Nakashima[9] who introduced the ITOX procedure and Ogura[11] who introduced a very slow ramp rate during high temperature annealing.

In the past, some researchers have noticed the importance of appropriate matches of dose-energy combinations on the formation of high-quality low-dose SIMOX materials,[1–3,7] but detailed study is lacking. Study of the microstructure evolution of the as-implanted wafers indicates

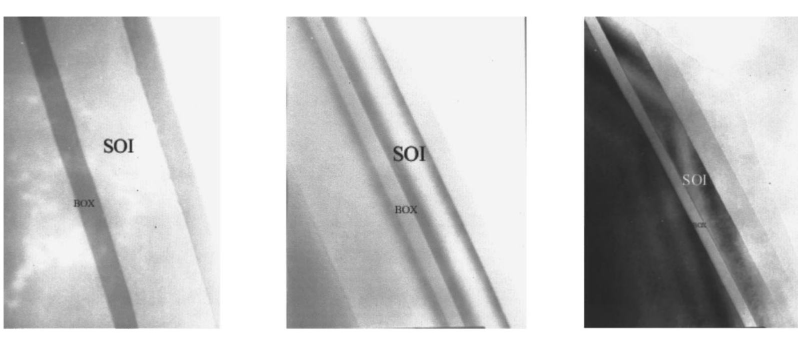

FIG. 2. XTEM micrographs of samples (a) S1, (b) S9, and (c) S12.

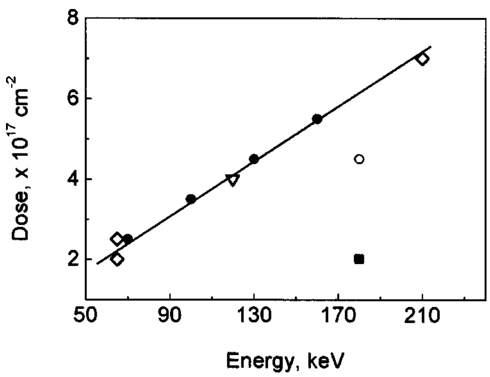

FIG. 3. Plot of a series of good dose-energy matches for the formation of high-quality low-dose SIMOX materials.

for those which have a damaged and disordered layer containing many multiple faulted defects present at a depth of damage peak (D_p) (seen in Fig. 4, the as-implanted sample implanted at 100 keV with the dose of 3.5×10^{17} cm^{-2}) are likely to form a continuous BOX layer with a minimal number of detectable silicon islands, while those which have laminar structures of damaged silicon are unlikely to form a high integrity BOX layer (in the present study, the as-implanted samples outside the optimum dose-energy match have such structures). It is suggested that the formation of Si islands is closely related to the laminar SiO_2/Si/SiO_2 structural configuration. A plausible explanation for this structural phenomenon is the low diffusivity of Si in SiO_2 that makes the trapped Si difficult to migrate to the surface or to the substrate which acts as a natural sink. Thus, this trapped Si recombines to form Si islands during the annealing. However, the laminar structure would form during consequent high temperature annealing, and the formation is correlated with the dose-energy match.[3,8] Within optimum dose-energy matches, the oxidation of silicon between the laminate and the horizontal growth of laminate oxide precipitates would simultaneously complete, and then form a continuous BOX layer with minimal detectable silicon islands.[1,8] Otherwise, many silicon islands would form. The effect of the dose-energy match on the microstructure is that the as-implanted oxygen profile has a crucial role in the subsequent development of the microstructure. This profile, on the other hand, is a function of the implantation energy-dose match. The postimplantation annealing, however, also plays an important role for the completion of the final phase of the microstructures because the mass transport of oxygen is driven not only by implanted energy, but also by the thermal energy of annealing.[3]

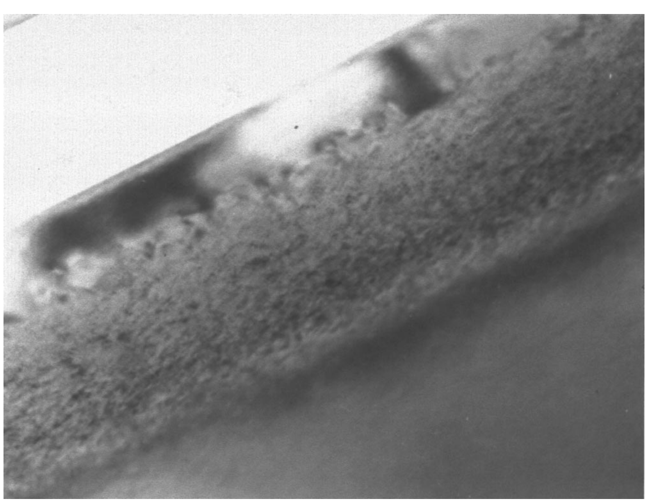

FIG. 4. Typical XTEM microphotograph of the as-implanted low-dose wafer likely to form a high-integrity BOX layer.

In summary, the present study reveals a method to directly form high-quality low-dose SIMOX materials from a good dose-energy match. The higher the oxygen dose, the higher the implanted energy required for the formation of low Si-islands BOX layer. For samples implanted at the energies of 160 keV, 130 keV, 100 keV, and 70 keV, the respective optimum doses are 5.5×10^{17} cm^{-2}, 4.5×10^{17} cm^{-2}, 3.5×10^{17} cm^{-2}, and 2.5×10^{17} cm^{-2}. The effect of dose-energy match is due to the oxygen profile in the as-implanted materials, which is optimized by the dose-energy match. This work also indicates a possibility to directly fabricate ultrathin SIMOX materials with ultrathin SOI and BOX layers by selecting an optimum low energy, low-dose implantation.

This work is supported by the National Science Foundation of China (Grant No. 59925205), Shanghai Government Fund for Development of Science and Technology (Grant No. 99XD 14029), and the Knowledge Innovation, Project of Chinese Academy of Sciences.

[1] S. Nakashima and K. Izumi, J. Mater. Res. **8**, 523 (1993).
[2] Y. Li, J. A. Kilner, R. J. Chater, P. L. F. Hemment, A. Nejim, A. K. Robinson, K. J. Reeson, C. D. Marsh, and G. R. Booker, J. Electrochem. Soc. **140**, 1780 (1993).
[3] J. Jiao, B. Johnson, S. Seraphin, M. J. Anc, R. P. Dolan, and B. F. Cordts, Mater. Sci. Eng., B **72**, 150 (2000).
[4] F. Namavar, B. Buchanan, E. Cortesi, and P. Sioshansi, Mater. Res. Soc. Symp. Proc. **147**, 235 (1992).
[5] M. Alles and W. Krull, Solid-State Electron. **39**, 499 (1995).
[6] A. Matsumura, K. Kawamura, I. Hamaguchi, S. Takayama, Y. Yano, and Y. Nagatake, J. Mater. Sci.: Mater. Electron. **10**, 365 (1999).
[7] A. Auberton-Herve, A. Wittkower, and B. Aspar, Nucl. Instrum. Methods Phys. Res. B **96**, 420 (1995).
[8] M. Chen, J. Chen, W. Zheng, L. Li, H. C. Mu, Z. X. Lin, Y. H. Yu, and X. Wang, J. Vac. Sci. Technol. B **19**, 337 (2001).
[9] S. Nakashima, T. Katayama, Y. Miyamura, A. Matsuzaki, M. Taoka, D. Ebi, M. Imai, K. Izumi, and N. Owada, J. Electrochem. Soc. **143**, 244 (1996).
[10] www.ibis.com
[11] A. Ogura and H. Ono, Appl. Surf. Sci. **159**, 104 (2000).
[12] S. Nakashima, M. Harada, and T. Tsuchiya, IEEE 1993 International SOI Conference Proceedings, 1993, p. 14.
[13] M. J. Anc, J. G. Blake, and T. Nakai, Electrochemical Society Proceedings, **99**, 51 (1999).