

# Low-energy separation by implantation of oxygen structures via plasma source ion implantation

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The initial results from an investigation into the feasibility of using plasma source ion implantation (PSII) to produce separation by implantation of oxygen structures in silicon are reported. Oxygen ions are implanted into *p*-type (111) oriented silicon wafers using a  $-30$  kV acceleration potential and an oxygen plasma at a pressure of 0.2 mTorr. The effects of ion dose and high-voltage pulse width were examined. Some of the implanted wafers were annealed. Both the as-implanted and annealed wafers were examined using secondary-ion-mass spectroscopy and Auger electron spectroscopy. The initial results show that oxygen can be implanted by PSII and suggest that a buried layer of silicon dioxide has been formed in the implanted wafers.

Recently, separation by implantation of oxygen (SIMOX), a silicon-on-insulator technology, has emerged as a promising candidate for complementary metal-oxide semiconductor applications.<sup>1,2</sup> SIMOX wafers have been used to fabricate devices which offer significant advantages in gain, speed, maximum operating temperature, and power consumption.<sup>3-6</sup> Conventionally, SIMOX wafers have been fabricated by high-dose ( $1.8 \times 10^{18}$  ions/cm<sup>2</sup>) and high-energy (150–200 keV) O<sup>+</sup> ion-beam implantation. A recent development in SIMOX technology, low-energy SIMOX (LES), uses low-dose ( $1-6 \times 10^{17}$  ions/cm<sup>2</sup>) and low-energy (20–80 keV) implantations to produce SIMOX wafers. It has been demonstrated that a SIMOX wafer with a 12.5 nm silicon overlayer and a 36 nm buried SiO<sub>2</sub> layer can be fabricated by implantation of O<sup>+</sup> at 20 keV with a total dose of  $1.5 \times 10^{17}$  ions/cm<sup>2</sup>, followed by high-temperature anneal.<sup>7</sup> Advantages of LES structures over conventional SIMOX structures are lower defect densities and lower production costs.<sup>1,8</sup>

SIMOX wafers are currently produced using conventional beam-line ion implanters. Plasma source ion implantation (PSII) is a potential alternative to beam-line implantation. Advantages of PSII over beam-line ion implantation include higher throughput, large area treatment, and less hardware. PSII also obviates the need for target rastering.<sup>9</sup> The principles of PSII operation have been discussed previously.<sup>10</sup> PSII operation can be briefly described as the application of a high negative voltage pulse to a target substrate immersed in a plasma, resulting in the motion of ions toward and electrons away from the biased electrode. The

accelerated ions are then implanted into the target.

In this letter, results of oxygen implantation into silicon wafers using PSII are given. The effects of ion dose and target bias pulse width are examined. These results are the initial findings from a feasibility study of using PSII to create LES wafers.

The samples were 3 in. boron-doped (111) oriented silicon wafers with a resistivity of 7.5–15  $\Omega$  cm. Each wafer was loaded into the PSII chamber immediately after opening the wafer package. The chamber was pumped down to a pressure of  $2-5 \times 10^{-6}$  Torr, and Ar sputtering ( $-10$  kV stage pulses, 0.5 mTorr, 20 min) was used to clean the Si surface, removing the thin native oxide layer. An oxygen plasma was generated from a filament source. Oxygen implantation at a target bias of  $-30$  kV immediately followed. During implantation, the oxygen pressure was maintained at 0.2 mTorr. In the oxygen plasma, it is estimated that 80% of the oxygen ions are O<sub>2</sub><sup>+</sup> with the remaining 20% O<sup>+</sup>. The fact that O<sub>2</sub><sup>+</sup> is the dominant implanted ion species and not O<sup>+</sup> (typical of conventional beam-line implantation) is not a strong concern. It has been shown that an implantation of O<sub>2</sub><sup>+</sup> at 60 keV gives a similar oxygen profile in silicon as an O<sup>+</sup> implantation at 30 keV.<sup>9</sup> Ion doses were controlled by the frequency, duty cycle, and total number of target bias pulses. Table I

TABLE I. Implantation and anneal conditions for silicon wafer samples.

Sample No.	1	2	3	4
Ion dose (ions/cm <sup>2</sup> )	$1.0 \times 10^{17}$	$5.5 \times 10^{16}$	$3.3 \times 10^{16}$	$3.3 \times 10^{16}$
Pulse width ( $\mu$ s)	40	40	40	10
Anneal temp ( $^{\circ}$ C)	...	1300	1080	1080
Anneal ambient	...	N <sub>2</sub> +0.138% O <sub>2</sub>	N <sub>2</sub>	N <sub>2</sub>
Anneal time (h)	...	6	7	7

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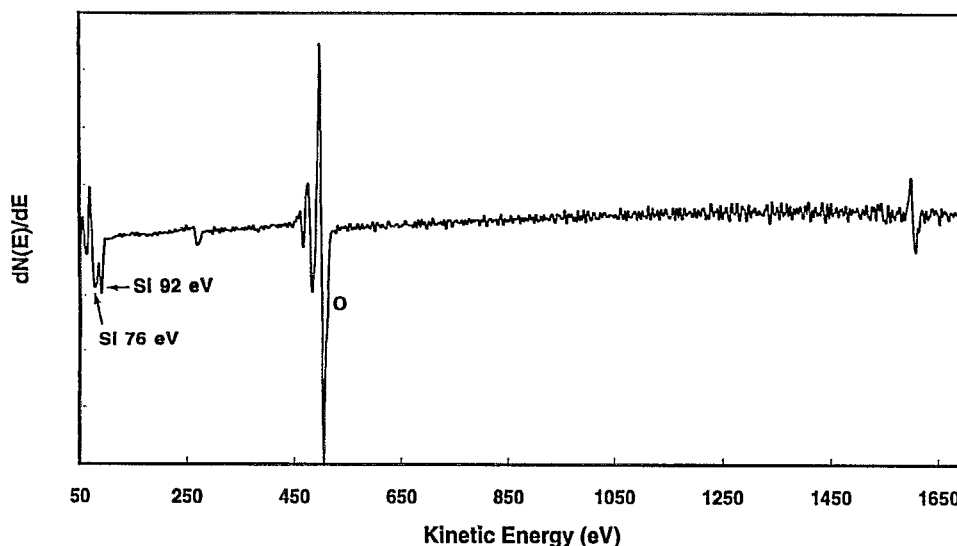


FIG. 1. Auger electron spectrum from sample 3 (oxygen implanted at  $-30$  kV,  $40 \mu\text{s}$  stage pulses, fill pressure of  $0.2$  mTorr, and with an ion dose of  $3.3 \times 10^{16} \text{ cm}^{-3}$ ).

lists the implantation and anneal conditions for the four samples studied. During implantation, the sample stage was water cooled, keeping the sample temperature below  $100^\circ\text{C}$ . Both the as-implanted wafers and annealed wafers were subsequently examined by secondary-ion-mass spectroscopy (SIMS) and Auger electron spectroscopy (AES).

Figure 1 shows the AES spectrum from the surface of sample 3. Standard AES spectra shows that peaks at  $76$  and  $92$  eV correspond to Auger electrons from silicon in  $\text{SiO}_2$  and pure silicon, respectively. Both peaks are observed in Fig. 1. This result suggests that there are some silicon atoms left on the surface. SIMS analysis of samples 2, 3, and 4 also indicates that the surfaces have a composition of  $\text{SiO}_x$  with  $x < 2$ . The chemical state of the silicon atoms, i.e., whether these atoms are in a Si- $\text{SiO}_2$  solid solution or in a mixture of crystalline Si grains and amorphous  $\text{SiO}_2$ , is still to be identified. In the AES spectrum from the surface of sample 1, only the  $76$  eV peak is observed, showing that almost all of the silicon atoms on the surface have been incorporated into the  $\text{SiO}_2$  compound.

Figure 2 shows the oxygen concentration profiles of sample 2 prior to anneal as a function of sputter depth from SIMS analysis. The oxygen concentration is almost uniform (about  $4 \times 10^{22} \text{ cm}^{-3}$ ) from the near surface to approximately  $45$  nm in depth. Based on the fact that the oxygen concentration in stoichiometric  $\text{SiO}_2$  should be  $\sim 4 \times 10^{22} \text{ cm}^{-3}$ , one may infer that  $\text{SiO}_2$  has formed in the near-surface region of uniform oxygen concentration between  $0$  and  $60$  nm in Fig. 2. The oxygen concentration profile for an implanted and annealed specimen of sample 2 is shown in Fig. 3. It is interesting that most of the oxygen in the near-surface region has diffused out in the annealed sample, leaving a thin Si layer of low oxygen content on the surface and a thin  $\text{SiO}_2$  layer underneath. In annealed sample 4, a similar phenomenon was observed by SIMS, except that the top Si layer was thinner than that of sample 2, which probably is due to the lower anneal temperature. These results indicate that buried

$\text{SiO}_2$  layers in Si substrates can be formed by PSII of oxygen followed by thermal anneal.

It is noted that the dose of  $1.0 \times 10^{17} \text{ cm}^{-3}$  in sample 1 may be too high for implantation using PSII with  $-30$  kV stage pulses, since almost all silicon atoms near the surface have been incorporated into  $\text{SiO}_2$ . By comparing SIMS data from sample 3 and 4, it is found that both the oxide layer thickness and the oxygen concentration in the implanted region in sample 4 are less, although the nominal doses for both the samples are the same. This suggests that shorter pulse widths ( $10 \mu\text{s}$ ) can result in fewer implanted ions and shallower projected range.

Previous beam-line implantation results have yielded thicker Si layers for similar ion energies and doses.<sup>7,8</sup> Two explanations are given for the shallower implantation depths for oxygen implantation using PSII.

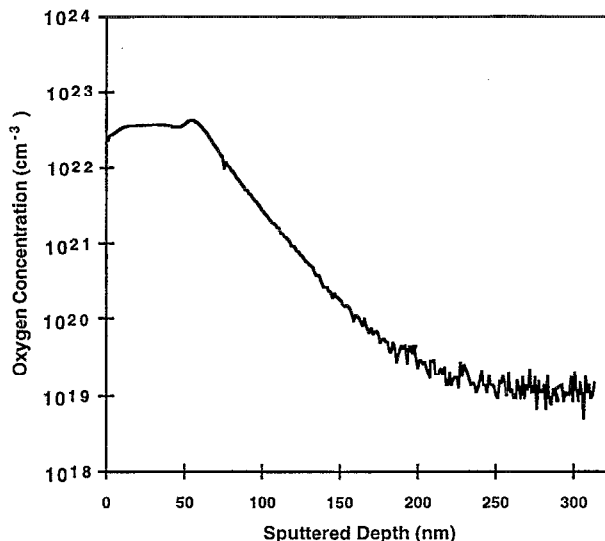


FIG. 2. SIMS oxygen concentration profile as a function of sputter depth in as-implanted sample 2 (oxygen implanted at  $-30$  kV,  $40 \mu\text{s}$  stage pulses, fill pressure of  $0.2$  mTorr, and an ion dose of  $3.3 \times 10^{16} \text{ cm}^{-3}$ ).

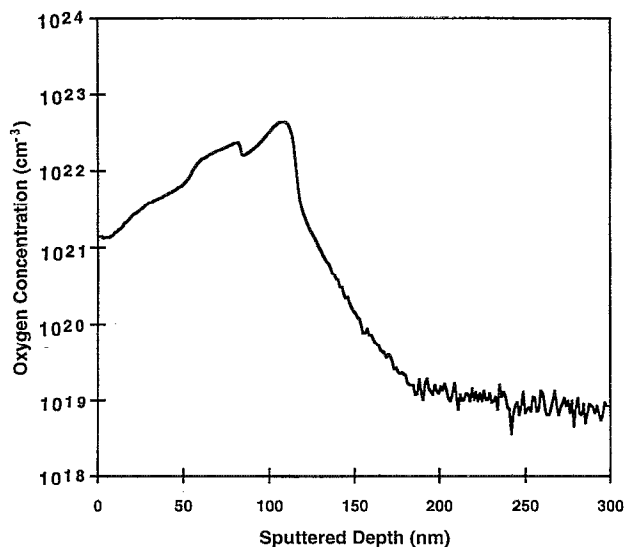


FIG. 3. SIMS oxygen concentration profile as a function of sputter depth in annealed sample 2 (oxygen implanted with  $-30$  kV,  $10 \mu\text{s}$  stage pulses, fill pressure of  $0.2$  mTorr, and an ion dose of  $3.3 \times 10^{16} \text{ cm}^{-2}$ ).

First, the ion energy is relatively low. Since the majority of ion species in our PSII system is  $\text{O}_2^+$  implanted with stage pulses of  $-30$  kV, the implantation energy per oxygen atom is at most equivalent to that of  $\text{O}^+$  ions implanted with stage pulses of  $-15$  kV. As a result, the mean projected range ( $R_p$ ) could be very shallow (about  $33$  nm for amorphous Si, estimated from Ref. 11). If one deducts one half of the mean full range ( $R_f$  is approximately  $26$  nm, Ref. 11) from  $R_p$ , there would be only  $7$  nm of silicon left on the surface. From this point of view, it seems that greater stage pulses ( $-40$  to  $-60$  kV) should be used to achieve results equivalent to the previous ion-beam LES experiments.

The second explanation for the observed shallow implantation depth is that implanted ions using PSII are distributed among a range of energies. This energy spread gives rise to undesirable low-energy ions ( $<30$  keV). These low-energy ions can either implant in the near-surface region or sputter the target surface so that most of the surface silicon atoms are either oxidized or sputtered away. There are a number of possible causes for this ion energy spread. Varia-

tions of target bias potential during the pulse rise and fall times, as well as electrostatic charge-up of the substrate surface, can result in a significant number of low-energy implanted ions. Other possible sources of low-energy ions include ion-neutral charge exchange, a collisional sheath, and secondary electron excitation of ions in the sheath region. It remains to be determined which process significantly contributes to the energy spread. PSII process parameters will have to be optimized to reduce the energy spread.

In summary, an investigation into the feasibility of using PSII for creation of LES structures has been initiated. Results demonstrate the ability to implant oxygen into silicon wafers using PSII. SIMS analysis indicates that a buried  $\text{SiO}_2$  layer is formed in implanted and annealed wafers. The oxide thickness and oxygen concentration profile is dependent upon ion dose, ion energy, and target bias potential pulse width. The results suggest that a higher target potential along with control of the energy spread will be required to produce higher quality LES wafers using PSII.

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- <sup>1</sup> J. O. Colinge, *Silicon-On-Insulator Technology: Materials of VLSI* (Kluwer Academic, Boston, 1991).
- <sup>2</sup> W. M. Huang, K. Klein, M. Grimaldi, M. Racanelli, S. Ramaswami, J. Taso, J. Foerstner, and B. Y. Hwang, *IEDM Tech. Dig.* 449 (1993).
- <sup>3</sup> Y. Omura and K. Izumi, *Proceedings of the 4th International Symposium on Silicon-On-Insulator Technology and Devices* (The Electrochemical Society, Pennington, NJ, 1990), p. 509.
- <sup>4</sup> T. Ohno, S. Matsumoto, and K. Izumi, *Electron. Lett.* **25**, 1071 (1989).
- <sup>5</sup> T. W. Houston, H. Lu, P. Mei, T. G. W. Blake, L. R. Blake, L. R. Hite, R. Sundaresan, M. Matloubian, W. E. Baily, J. Liu, A. Peterson, and G. Pollack, *IEEE SOS/SOI Technology Conference Proceedings*, 1989, p. 137 (unpublished).
- <sup>6</sup> T. Nishimura, Y. Yamaguchi, M. Shimizu, K. Tsukamoto, and Y. Akasada, *IEDM Tech. Dig.* 109 (1991).
- <sup>7</sup> F. Namavar, E. Cortesi, B. Buchana, and P. Sioshansi, *IEEE SOS/SOI Technology Conference Proceedings*, 1989, p. 117 (unpublished).
- <sup>8</sup> F. Namavar, E. Cortesi, B. Buchana, and P. Sioshansi, *IEEE SOS/SOI Technology Conference Proceedings*, 1989, p. 117 (unpublished).
- <sup>9</sup> N. Mayyappan and T. Nakato, presented at the *IEEE SOS/SOI Technology Conference*, 1993 (unpublished).
- <sup>10</sup> J. R. Conrad, J. L. Radtke, R. A. Dodd, F. J. Worzala, and N. C. Tran, *J. Appl. Phys.* **62**, 11 (1987).
- <sup>11</sup> J. E. Gibbons, W. S. Johnson, and S. W. Mylroie, *Projected Range Statistics* (Dowden, Hutchinson and Ross, Inc., Pennsylvania, 1975).