Author(s): J. P. Zhang, Y. S. Tang, A. K. Robinson, U. Bussmann, P. L. F. Hemment, B. J. Sealy, S. M. Newstead, A. R. Powell, T. E. Whall, and E. H. C. Parker
Article Title: Behavior of high dose O^+-implanted Si/Ge/Si structures
Year of publication: 1990
Link to published version: http://dx.doi.org/ 10.1063/1.103395
Publisher statement: none

Behavior of high dose O^+-implanted Si/Ge/Si structures

J. P. Zhang,[a] Y. S. Tang, A. K. Robinson, U. Bussmann, P. L. F. Hemment,
and B. J. Sealy
*Department of Electronic and Electrical Engineering, University of Surrey, Guildford, Surrey GU2 5XH,
United Kingdom*

S. M. Newstead, A. R. Powell, T. E. Whall, and E. H. C. Parker
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

(Received 19 April 1990; accepted for publication 25 June 1990)

The synthesis of a buried oxide layer in multilayer Si/Ge/Si structures by the implantation of high doses of 200 keV O^+ ions is studied by Rutherford backscattering analysis. The presence of Ge is found to have a minimal effect upon the mass transport of excess oxygen and interstitial silicon. Infrared transmission spectroscopy and x-ray photoelectron spectroscopy confirm that the oxygen atoms bond preferentially to silicon forming silicon dioxide and SiO_x, where $x < 2$, with no evidence for Ge—O bonding.

Separation by implanted oxygen (SIMOX)[1] is one of the most promising materials technologies for the preparation of silicon on insulator (SOI) substrates for small geometry complementary metal-oxide-semiconductor (CMOS) circuits.[2] The success achieved using this technology has focused attention on possible device applications of other materials and structures also formed by ion beam synthesis. Examples of compounds currently being studied include Si_3N_4, SiC, and silicides,[2] which all involve the implantation of high doses of reactive ions into bulk silicon.

Advances in layer growth technologies now enable high quality heteroepitaxial structures to be formed and among these, the SiGe alloy system currently is attracting much attention because of its compatibility with bulk silicon processing and great potential for high-speed electronic and optoelectronic devices.[3] In this letter we report the first experiments to explore the possibility of applying SIMOX technology to the SiGe system and describe experiments in which high doses of 200 keV O^+ ions have been implanted into Si/Ge/Si layered structures.

Samples were grown by molecular beam epitaxy (MBE) on 15–20 Ω cm *p*-type (100) silicon at a growth temperature of 575 °C in a VG Semicon V80 system. First, a silicon buffer layer was grown on the substrate followed by a 500 Å layer of Ge and terminated with a top layer of silicon. This silicon overlayer had a thickness of either 1000 Å (wafer 109/11) or 3500 Å (wafer 109/9) as detailed in Table I. These thick layers were expected to be unstrained (fully relaxed) and this was confirmed by Rutherford backscattering (RBS) and channeling measurements. Subsequently the wafers were implanted with 400 keV O_2^+ ions to doses of 0.6×10^{18}, 1.2×10^{18}, and 1.8×10^{18} cm^{-2} at a substrate temperature of about 525 °C. Details of the implantation procedure are reported elsewhere.[4] The composition of the samples was determined by 1.5 MeV He^+ RBS, while the chemical environment of the implanted oxygen was ascertained by infrared (IR) transmission spectroscopy, using a Perkin–Elmer 577 grating spectrophotometer. Selected samples were further examined by x-ray photoelectron spectroscopy (XPS) using a VG Scientific ESCALAB MKII system and secondary-ion mass spectrometry (SIMS).

Figure 1 shows nonchanneling RBS spectra from samples prepared from wafer 109/11 with a 1000 Å silicon overlayer. The curves labeled (i), (ii), and (iii) are from samples "as grown", implanted with 0.6×10^{18} O^+ cm^{-2} and 1.8×10^{18} cm^{-2} respectively. The presence of the buried Ge layer may be inferred from the yield deficiency centered on channel 260 while the Ge depth distribution may be determined from the peak centered on channel 380. The movement of these features to higher energy has a linear dependence upon O^+ dose (Table I) and is due to surface sputtering at a rate of 0.2–0.25 atoms per oxygen particle. For the highest dose, sputtering removes the silicon overlayer and causes a 30% loss of Ge. Collisional processes lead also to a broadening of the Ge layer (Table I). The yield deficiency between channels 160 and 250 is due to the implanted oxygen, and by comparison of these and other spectra with data from SIMOX samples (an example is shown by the dashed line), it is evident that the redistribution of excess oxygen has the same evolution as found in SIMOX,[5] despite the presence of the Ge layer.

Figure 2 shows RBS spectra from samples prepared from wafer 109/9 in which the low-dose oxygen depth profile is centered on the 500 Å Ge layer below the 3500 Å layer of silicon. In these spectra the silicon yield deficiency between channels 160 and 250, which is wider than in Fig. 1, arises from the overlap of the individual deficiencies due to the presence of the implanted oxygen and buried layer of Ge. The apparent movement of the Ge layer towards the surface due to the reduction in thickness of the silicon overlayer (Table I) shows the same dose dependence as in specimens 109/11 and, therefore, is assumed to be due solely to sputtering. Broadening of the Ge depth profile is greater, by about 50%, than in specimen 109/11, as listed in Table I.

The layer thicknesses have been chosen so that the

---

[a] Permanent address: Institute of Semiconductors, Academia Sinica, P. O. Box 912, Beijing 100 083, People's Republic of China.

TABLE I. Composition of the Si/Ge/Si structures before and after implantation with 200 keV O^+ ions.

Spec. No.	Nominal structure	O^+ dose ($10^{18}/cm^2$)	Thickness of Si overlayer $\times 10^{18}$ (atoms/cm^2)	Width of Ge layer arb units (channels)	Areal density of Ge layer (10^{18} Ge cm^{-2})
109/11					
(a)	1000 Å Si	0.6	0.39	17	0.19
(b)	500 Å Ge	1.8	0.17	14	0.13
(c)	250 Å Si buffer	1.2	0.33	20	0.18
(d)	Si substrate	···	0.54	12	0.19
109/9					
(a)	3500 Å Si	0.6	1.7	20	0.19
(b)	500 Å Ge	1.8	1.5	27	0.19
(c)	250 Å Si buffer	1.2	1.6	26	0.19
(d)	Si substrate	···	1.8	13	0.19

behavior of the implanted oxygen in these relaxed Si/Ge/Si multilayer structures may be followed. The synthesis of SiO_2 in bulk silicon (SIMOX) is controlled by the processes of sputtering, swelling, and diffusion.[5,6] Growth occurs by internal oxidation, mainly at the upper SiO_2/Si interface,[5] and is accompanied by the ejection of Si_{Int}, which then migrate by radiation-enhanced diffusion towards the surface where they are annihilated.[7] Van Ommen[8] has proposed that the observed retarded oxidation at the lower interface of SIMOX samples is due to the presence of excess interstitials which lie outside the radiation-damaged profile and thus do not experience enhanced diffusion. In common with SIMOX, these Si/Ge/Si samples show saturation of the oxygen concentration at the value for stoichiometric SiO_2 and oxide growth preferentially at the upper interface (Figs. 1 and 2). As the presence of the Ge layer is not inhibiting the process of internal oxidation, it is concluded that the transport of ejected Si_{Int} to the free surface during implantation is not significantly impeded.

The oxygen concentration and deposited energy densities in the vicinity of the Ge layers in these two sets of samples are markedly different, due to the different thicknesses of the silicon overlayer, and this enables the extent to which internal oxidation and collisional processes control the final structure to be ascertained. For example, atomic mixing is more pronounced in specimen 109/9, showing a broadening which is consistent with the expected noninteger power dependence upon collisional energy density.[9] In sample 109/11 the process of mixing redistributes the Ge and in so doing forms a broad SiGe layer with a maximum Ge concentration of 50% atomic and a graded interface extending 1500 Å into the silicon overlayer.

Chemical changes in these samples and other control samples, which consisted of unannealed SIMOX material and bulk Ge implanted with 1.8×10^{18} O^+ cm^{-2} at 300 keV, respectively, have been determined by IR transmission spectroscopy and XPS analysis. Figure 3 shows typical IR spectra from samples 109/9 (a), (b), and (c). Three absorption bands are evident whose intensity increases monotonically with dose. The strongest band, which is centered at a wave number of 1050 cm^{-1}, is due to the stretching mode of the Si—O—Si bonding unit, a

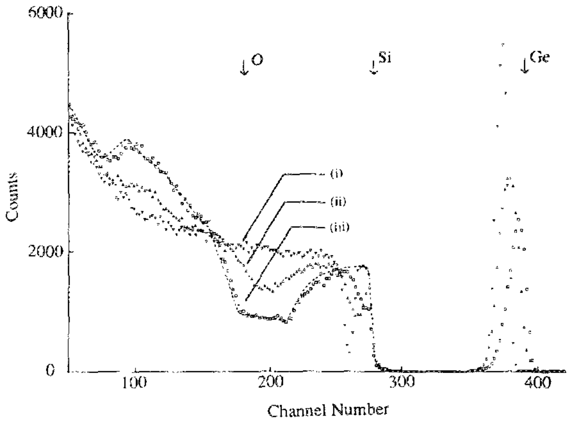

FIG. 1. Nonchanneling 1.5 MeV He^+ RBS spectra from samples prepared from wafer 109/11. These have been implanted with 400 keV O_2^+ at doses of (i) 0, (ii) 0.6×10^{18} cm^{-2}, and (iii) 1.8×10^{18} cm^{-2}. The spectra from an unannealed SIMOX sample implanted with 1.78×10^{18} O^+ cm^{-2} is included (dashed).

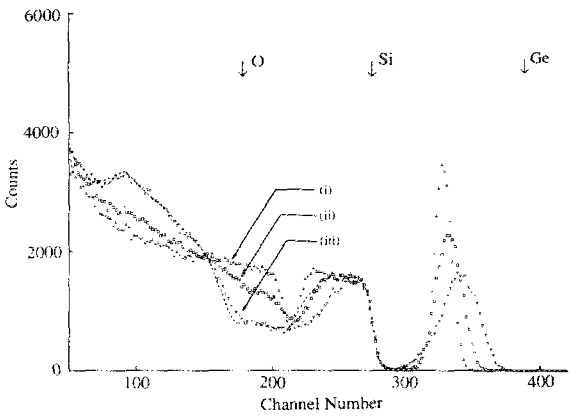

FIG. 2. Nonchanneling 1.5 MeV He^+ RBS spectra from samples prepared from wafer 109/9, which have been implanted with (i) 0, (ii) 0.6×10^{18} cm^{-2}, and (iii) 1.8×10^{18} cm^{-2}. The spectrum from a SIMOX sample (dashed line) is included as a reference.

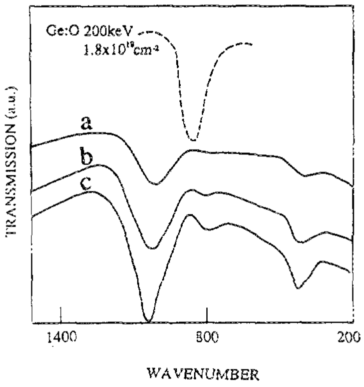

FIG. 3. Infrared transmission spectra from samples 109/9 (a), (b), and (c). The spectrum from a bulk Ge sample implanted with 1.8×10^{18} O^+ cm^{-2} at 300 keV is included.

configuration associated with SiO_x where $x\leqslant2$. The extent of the shift of this band from the value for a thermal oxide ($1089\ cm^{-2}$) coupled with an increase in width is indicative of comprehensive strain and the presence of substoichiometric oxides.[10] The absorption band for the implanted bulk Ge sample, which is due to the presence of Ge—O bonds, is shown also in Fig. 3. As this band is not present in the spectra from the Si/Ge/Si samples it is concluded that Ge—O bonds have not been formed. The absence of oxides in germanium and the existence of both stoichiometric and substoichiometric silicon oxides[10] in these samples was subsequently confirmed by XPS analysis. Detailed O and Ge depth profiles extracted from the RBS data showed that the Ge is localized in a layer just above the synthesized oxide. The absence of Ge in this buried oxide was confirmed by SIMS analysis and is consistent with Patten *et al.*,[11] who report the rejection of Ge from thermally grown oxides on SiGe alloys.

Thus it is found that the presence of a layer of elemental Ge buried within the silicon matrix plays a minimal role in controlling the mass transport and incorporation of excess oxygen implanted into the layered structures. Channeling analysis shows that the single-crystal overlayer is highly disordered and currently the annihilation of defects and redistribution of the Ge and O during high-temperature annealing is being studied. This experiment is a precursor to a detailed study of oxide synthesis by O^+ implantation into a SiGe alloy and shows that the physical description of the evolution of SIMOX structures during implantation is appropriate also to the Si/Ge system.

The authors thank the staff of the D. R. Chick Accelerator Laboratory, University of Surrey, H. Liu and G. J. Buist, for assistance in carrying out these experiments. This work is supported in part by the U.K. Science and Engineering Research Council.

[1] K. Izumi, M. Doken, and H. Ariyashi, Electron. Lett. **14**, 594 (1978).
[2] See for example, J. C. Sturm, C. K. Chen, L. Pfeiffer, and P. L. F. Hemment, eds. *Proceedings of the Symposium of the Materials Research Society, Pittsburgh, 1987*, (Materials Research Society, Pittsburgh, 1987), Vol. 107.
[3] T. C. McGill, R. H. Miles, R. J. Hauenstein, and O. J. March, in *Proceedings of the Second International Symposium on Si Molecular Beam Epitaxy*, edited by J. C. Bean and L. J. Schowalter (Electrochemical Society, Pennington, NJ, 1988), p. 1.
[4] P. L. F. Hemment, E. A. Maydell-Ondrusz, K. G. Stephens, J. B. Butcher, D. Ioannou, and J. Alderman, Nucl. Instrum. Methods **209/210**, 157 (1983).
[5] J. A. Kilner, R. J. Chater, P. L. F. Hemment, R. F. Peart, E. A. Maydell-Ondrusz, M. R. Taylor, and R. P. Arrowsmith, Nucl. Instrum. Methods Phys. S. B **7/8**, 293 (1985).
[6] U. Bussman and P. L. F. Hemment, Nucl. Instrum. Methods B **47**, 22 (1990).
[7] J. Stoemenos, *Mechanisms of Buried Oxide Formation by Implanted Oxygen in Ion Implantation in Semiconductors*, edited by X. Stievenard and Bourgoin (Trans. Tech. Publications, Aebermannsdorf, Switzerland, 1988), p. 115.
[8] A. H. van Ommen, Nucl. Instrum. Methods Phys. Rev. B **39**, 194 (1989).
[9] F. K. LeGoues, R. Rosenberg, T. Nguyen, F. Himpsel, A. Taleb-IbraHimi, and B. S. Meyerson, J. Appl. Phys. **65**, 1724 (1989).
[10] G. Harbeke, E. F. Steigmeier, P. L. F. Hemment, and K. J. Reeson, Semicond. Sci. Technol. **2**, 687 (1987).
[11] G. L. Patton, S. S. Iyer, S. L. Delage, E. Ganin, and R. C. McIntosh, Proc. Symp. Mater. Res. Soc. **97**, 295 (1987).