Science and Technology of Semiconductor-On-Insulator Structures and Devices Operating in a Harsh Environment

NATO Science Series

A Series presenting the results of scientific meetings supported under the NATO Science Programme.

The Series is published by IOS Press, Amsterdam, and Kluwer Academic Publishers in conjunction with the NATO Scientific Affairs Division

Sub-Series

I. Life and Behavioural Sciences	IOS Press
II. Mathematics, Physics and Chemistry	Kluwer Academic Publishers
III. Computer and Systems Science	IOS Press
IV. Earth and Environmental Sciences	Kluwer Academic Publishers
V. Science and Technology Policy	IOS Press

The NATO Science Series continues the series of books published formerly as the NATO ASI Series.

The NATO Science Programme offers support for collaboration in civil science between scientists of countries of the Euro-Atlantic Partnership Council. The types of scientific meeting generally supported are "Advanced Study Institutes" and "Advanced Research Workshops", although other types of meeting are supported from time to time. The NATO Science Series collects together the results of these meetings. The meetings are co-organized bij scientists from NATO countries and scientists from NATO's Partner countries – countries of the CIS and Central and Eastern Europe.

Advanced Study Institutes are high-level tutorial courses offering in-depth study of latest advances in a field.
Advanced Research Workshops are expert meetings aimed at critical assessment of a field, and identification of directions for future action.

As a consequence of the restructuring of the NATO Science Programme in 1999, the NATO Science Series has been re-organised and there are currently Five Sub-series as noted above. Please consult the following web sites for information on previous volumes published in the Series, as well as details of earlier Sub-series.

http://www.nato.int/science
http://www.wkap.nl
http://www.iospress.nl
http://www.wtv-books.de/nato-pco.htm

Series II: Mathematics, Physics and Chemistry – Vol. 185

Science and Technology of Semiconductor-On-Insulator Structures and Devices Operating in a Harsh Environment

edited by

Denis Flandre

Université Catholique de Louvain,
Microelectronics Laboratory,
Louvain-la-Neuve, Belgium

Alexei N. Nazarov

National Academy of Science of Ukraine,
Institute of Semiconductor Physics,
Kyiv, Ukraine

and

Peter L.F. Hemment

University of Surrey,
School of Electronics and Physical Sciences,
Guildford, U.K.

Kluwer Academic Publishers

Dordrecht / Boston / London

Published in cooperation with NATO Scientific Affairs Division

Proceedings of the NATO Advanced Research Workshop on
Science and Technology of Semiconductor-On-Insulator Structures and Devices
Operating in a Harsh Environment
Kiev, Ukraine
26–30 April 2004

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN 1-4020-3012-6 (PB)
ISBN 1-4020-3011-8 (HB)
ISBN 1-4020-3013-4 (e-book)

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Sold and distributed in North, Central and South America
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Printed on acid-free paper

All Rights Reserved
© 2005 Kluwer Academic Publishers
No part of this work may be reproduced, stored in a retrieval system, or transmitted
in any form or by any means, electronic, mechanical, photocopying, microfilming,
recording or otherwise, without written permission from the Publisher, with the exception
of any material supplied specifically for the purpose of being entered
and executed on a computer system, for exclusive use by the purchaser of the work.

Printed in the Netherlands.

TABLE OF CONTENTS

PREFACE .... - ix

TECHNOLOGY AND ECONOMICS

High temperature electronics – cluster effects .... - 1
C. Johnston, A. Crossley

On the evolution of SOI materials and devices .... - 11
J.P. Colinge

SOI Technology as a basis for microphotonic-microelectronic integrated devices .... - 27
M.Yu. Barabanenkov, V.V. Aristov, V.N. Mordkovich

SOI MATERIAL TECHNOLOGIES

Smart Cut Technology: the path for advanced SOI substrates .... - 39
H. Moriceau, C. Lagahe-Blanchard, F. Fournel, S. Pocas, E. Jalaguier, P. Perreau, C. Deguet, T. Ernst, A. Beaumont, N. Kernevez, J.M. Hartman, B. Ghyselen, C. Aulnette, F. Letertre, O. Rayssac, B. Faure, C. Richtarch, I. Cayrefourq

Porous silicon based SOI: history and prospects.................................... - 53
V. Bondarenko, G. Troyanova, M. Balucani, A. Ferrari

Achievement of SiGe-on-insulator technology .... - 65
Y. Ishikawa, N. Shibata, S. Fukatsu

CVD diamond films for SOI technologies .... - 77
V. Ralchenko, T. Galkina, A. Klokov, A. Sharkov, S. Chernook, V. Martovitsky

Radical beam quasiepitaxy technology for fabrication of wide-gap semiconductors on insulator .... - 85
G. Natsvlishvili, T. Butkhuzi, M. Sharvashidze, L. Trapaidze, D. Peikrishvili

Impact of hydrostatic pressure during annealing of Si:O on creation of SIMOX-like structures .... - 91
A. Misiuk, J. Ratajczak, J. Kątcki, I.V. Antonova

SiO_2 and Si_3N_4 phase formation by ion implantation with in-situ ultrasound treatment .... - 97
O. Martinyuk, D. Mazunov, V. Melnik, Ya. Olikh, V. Popov, B. Romanyuk, I. Lisovskii

Fabrication and characterisation of Silicon On Insulator substrates incorporating thermal vias ... - 103
M.F. Bain, P. Baine, D.W. McNeill, G. Srinivasan, N. Jankovic, J. McCartney, R.A. Moore, B.M. Armstrong, H.S. Gamble

RELIABILITY AND OPERATION OF SOI DEVICES IN HARSH ENVIRONMENT

Reliability and electrical fluctuations in advanced SOI CMOS devices ... - 109
J. Jomaah, F. Balestra

Hydrogen and high-temperature charge instability of SOI structures and MOSFETs ... - 121
A.N. Nazarov

Recent advances in SOI MOSFET devices and circuits for ultra-low power / high temperature applications ... - 133
D. Levacq, V. Dessard, D. Flandre

Silicon-on-insulator circuits for application at high temperatures ... - 145
V. Nakov, D. Nuernbergk, S.G.M. Richter, S. Bormann, V. Schulze, S.B. Richter

High-voltage SOI devices for automotive applications ... - 155
J. Olsson

Heat generation analysis in SOI LDMOS power transistors ... - 167
J. Roig, D. Flores, J. Urresti, S. Hidalgo, J. Rebollo

Novel SOI MOSFET structure for operation over a wide range of temperatures ... - 179
V.Ya. Uritsky

MOSFETs scaling down: advantages and disadvantages for high temperature applications ... - 185
V. Kilchytska, L. Vancaillie, K. de Meyer, D. Flandre

Temperature dependence of RF losses in high-resistivity SOI substrates ... - 191
D. Lederer, J.-P. Raskin

RADIATION EFFECTS

Review of radiation effects in single- and multiple-gate SOI MOSFETs .... - 197
S. Cristoloveanu

Radiation effects in SOI: Irradiation by high energy ions and electrons............ - 215
I.V. Antonova, J. Stano, O.V. Naumova, V.A. Skuratov, V.P. Popov

Radiation characteristics of short p-channel MOSFETs on SOI substrates .... - 221
A. Evtukh, A. Kizjak, V. Litovchenko, C. Claeys, E. Simoen

Total dose behavior of partially depleted DeleCut SOI MOSFETs .... - 227
O.V. Naumova, A.A. Frantzusov, I.V. Antonova, V.P. Popov

Radiation effect on electrical properties of fully-depleted UNIBOND SOI MOSFETs .... - 233
Y. Houk, A.N. Nazarov, V.I. Turchanikov, V.S. Lysenko, S. Adriaensen, D. Flandre

CHARACTERIZATION AND SIMULATION OF SOI DEVICES OPERATING UNDER HARSH ENVIRONMENT

Low cost high temperature test system for SOI devices............ - 241
G. Russell, Y. Li, H. Bahr

Characterization of carrier generation in thin-film SOI devices by reverse gated-diode technique and its application at high temperatures .... - 247
T.E. Rudenko, V.I. Kilchytska, D. Flandre

Back-gate induced noise overshoot in partially-depleted SOI MOSFETs............ - 255
N. Lukyanchikova, N. Garbar, A. Smolanka, E. Simoen, C. Claeys

NOVEL SOI DEVICES AND SENSORS OPERATING AT HARSH CONDITIONS

SiGe heterojunction bipolar transistors on insulating substrates .... - 261
S. Hall, O. Buiu, I.Z. Mitrovic, H.A.W. El Mubarek, P. Ashburn, M. Bain, H.S. Gamble, Y. Wang, P.L.F. Hemment, J. Zhang

Silicon-on-Insulator substrates with buried ground planes (GPSOI) ..... - 273
M. Bain, S. Stefanos, P. Baine, S.H. Loh, M. Jin, J.H. Montgomery, B.M. Armstrong, H.S. Gamble, J. Hamel, D.W. McNeill, M. Kraft, H.A. Kemhadjian

High-voltage high-current DMOS transistor compatible with high-temperature thin-film SOI CMOS applications .... - 279
P. Godignon, M. Vellvehi, D. Flores, J. Millán, L. Moreno Hagelsieb, D. Flandre

A novel low leakage EEPROM cell for application in an extended temperature range (-40 °C up to 225 °C) .... - 285
S. G. M. Richter, D. Kirsten, D.M. Nuernbergk, S.B.Richter

Design, fabrication and characterization of SOI pixel detectors of ionizing radiation .... - 291
D. Tomaszewski, K. Domański, P. Grabiec, M. Grodner, B. Jaroszewicz, T. Klatka, A. Kociubiński, M. Kozieł, W. Kucewicz, K. Kucharski, S. Kuta, J. Marczewski, H. Niemiec, M. Sapor, M. Szeleźniak

Polysilicon-on-insulator layers at cryogenic temperatures and high magnetic fields... - 297
A. Druzhinin, I. Maryamova, I. Kogut, Y. Pankov, Y. Khoverko, T. Palewski

Planar photomagnetic effect SOI sensors for various applications with low detection limit.. - 303
V.N. Dobrovolsky, V.K. Rossokhaty

Theoretical limit for the SiO_2 thickness in silicon MOS devices .... - 309
B. Majkusiak, J. Walczak

Compact model of the nanoscale gate-all-around MOSFET .... - 321
D. Jiménez, B. Iñíguez, J. J. Sáenz, J. Suñé, L. F. Marsal, J. Pallarès

Self-assembled semiconductor nanowires on silicon and insulating substrates: Experimental behavior... - 327
T. Kamins, S. Sharma, M. Saif Islam

Fabrication of SOI nano devices .... - 333
X. Tang, N. Reckinger, V.Bayot

KEYWORD INDEX .... - 345

AUTHOR INDEX .... - 347

PREFACE

This proceedings volume archives the contributions of the speakers who attended the NATO Advanced Research Workshop on "Science and Technology of Semiconductor-On-Insulator Structures and Devices Operating in a Harsh Environment" held at the Sanatorium Puscha Ozerna, Kyiv, Ukraine, from 25th to 29th April 2004.

The semiconductor industry has maintained a very rapid growth during the last three decades through impressive technological achievements which have resulted in products with higher performance and lower cost per function. After many years of development semiconductor-on-insulator materials have entered volume production and will increasingly be used by the manufacturing industry. The wider use of semiconductor (especially silicon) on insulator materials will not only enable the benefits of these materials to be further demonstrated but, also, will drive down the cost of substrates which, in turn, will stimulate the development of other novel devices and applications. In itself this trend will encourage the promotion of the skills and ideas generated by researchers in the Former Soviet Union and Eastern Europe and their incorporation in future collaborations.

This volume contains the extended abstracts of both oral and poster papers presented during the four-day meeting, under the headings of:

- Technology and Economics
- Semiconductor-On-Insulator Material Technologies
- Reliability and Operation of SOI Devices in a Harsh Environment
- Radiation Effects
- Characterization and Simulation of SOI Devices Operating in a Harsh Environment
- Novel SOI Devices and Sensors Operating under Harsh Conditions

These high-quality papers were presented by researchers from Japan, USA, European Union and the Eastern European countries of the Former Soviet Union, thereby fulfilling a further underlying objective of the Workshop which was to cement existing links established during the three previous NATO Silicon on Insulator Workshops held in Ukraine, in 1994, 1998, and 2000 and to develop new world-wide contacts between researchers in the attendees countries.

The meeting thus successfully achieved its scientific and networking goals and the attendees wish to express their gratitude to the NATO International Scientific Exchange Programme, whose financial support made the meeting possible, and to the National Academy of Science of Ukraine and the Science and Technology Centre of Ukraine who provided local support. The organizers offer their sincere thanks to Prof. V. Lysenko who worked unstintingly to guarantee the success of the Workshop. We would like to thank the agency "Optima" whose Director Mariya Miletska professionally helped us to organize this workshop. Our deep acknowledgements also go to Yu. Houk, Ya. Vovk, V. Stepanov, A. Rusavsky, Dr. A. Stronsky, Dr. G. Rudko, Dr. T. Rudenko, V. Torbin, V. Smirnaya, Dr. I. Tyagulsky, Dr. I. Osiyuk and Dr. A. Vasin for their clerical and technical assistance, which ensured the conference and social arrangements ran smoothly. A final special thanks to Dr. Valeria Kilchytska for her dedication in compiling this book and for very many other practical contributions.

Denis Flandre
Louvain-la-Neuve, Belgium

Alexei Nazarov
Kyiv, Ukraine

Peter Hemment
Guildford, UK

SIO_2 AND SI_3N_4 PHASE FORMATION BY ION IMPLANTATION WITH IN-SITU ULTRASOUND TREATMENT

O. Martinyuk[2], D. Mazunov[1], V. Melnik[1], Ya. Olikh[1], V. Popov[1], B. Romanyuk[1] and I. Lisovskii[1]

[1]*V. Lashkarev Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, 41 Prospect Nauki , Kyiv 03028, Ukraine*; [2]*National Technical University of Ukraine "Kiev Politechnikal Institute", 37 Prospect Peremogy, Kyev 03056, Ukraine*

Abstract: For stimulation of ultra-thin dielectric layer formation we used *in-situ* ultrasound (US) excitation of the silicon wafer during N^+ or O^+ ion implantation. ToF-SIMS dopant profiling and infrared transmission spectroscopy has been used to analyze the buried film structure and composition.. The US treatment during an implantation gives in more effective SiO_2 phase growth in the area of R_p-ΔR_p . The thickness of the buried layer is ~5 nm less in comparison with the case of implantation without US. For the samples implanted by nitrogen, ultrasonic treatment leads to shrinkage of nitrogen distribution profile and its shift to a surface.

Key words: Silicon-on-Insulator; Ion Implantation; Ultrasound Treatment; Point Defects; Buried Layer; Oxygen; Nitrogen.

1. INTRODUCTION

Silicon-On-Insulator (SOI) material synthesized by Separation by Implanted Oxygen (SIMOX) remains a leading candidate for advanced, large-scale, integrated circuit applications due to thickness uniformity and moderate defect density.[1] Presently, the most widely used SIMOX is material, typically produced by high-dose implantation of $1.8 \cdot 10^{18}$ cm^{-2} of O^{16} ions at ~600°C, which results in a buried oxide (BOX) layer thickness of ~300 nm. However, in the recent years, there has been a growing interest in low-dose SIMOX (dose <$1.0 \cdot 10^{18}$ cm^{-2}), with BOX layer thicknesses from 80 to 200 nm, because of potential technological and economic advantages over

D. Flandre et al. (eds.), Science and Technology of Semiconductor-On-Insulator Structures and Devices Operating in a Harsh Environment, 97-102.
© 2005 *Kluwer Academic Publishers. Printed in the Netherlands.*

high-dose SIMOX. At lower dose of $2 \cdot 10^{17}$ cm^{-2} a layer did not form, but only disjointed, isolated oxide precipitates are developed.[2]

To promote the formation of ultra-thin (<0.1 μm) BOX, the implantation process was modified to produce a microstructure, which promotes coalescence of the oxygen into a continuous layer.[3] The method which yielded the best results consists of a standard implantation at $3 \cdot 10^{17}$ cm^{-2} followed by a dose of 10^{15} cm^{-2} at room temperature.

Nucleation and growth of the SiO_2 precipitates depends on the set of factors, especially on the point defect concentration in the precipitate formation region. For example, it was shown in [4] that carbon enhances oxide precipitation via C_s-Si_i interaction. Reducing of the supersaturation of Si_i and the strain fields around precipitates implies the enhancement effect on oxide-precipitate growth.

Increase of the vacancy concentration in the region of precipitate nucleation and growth also stimulates these processes. The defect concentration may be changed by different ways: annealing in the various ambients, additional ion implantation, deposition of layers on the sample surface.

It is determined nowadays that ultrasound treatment (UST) influences the defect structure and electro-physical characteristics of silicon and silicon-based structures.[5] We had shown[4] that the use of *in situ* UST during the implantation process leads to the separation of point defects and accumulation of the vacancy clusters within the $R_p - \Delta R_p$ region. In the given paper we describe the investigations devoted to the UST influence on the buried SiO_2 and Si_3N_4 layer formation.

2. EXPERIMENTAL

(100) boron-doped Cz-silicon samples (10 $\Omega \cdot$cm) were mounted inside the implantation chamber on piezoelectric transducers via acoustic binders. The cell with a sample and US transducer in shown in Fig.1.

Ultrasound vibrations were generated in the wafer by operating the transducer in a resonance mode. The basic resonance frequency was of 6 MHz. The amplitude of the generated deformations did not exceed 10^{-5} of the lattice constant, corresponding to an acoustic power of 1 W$\cdot$cm^{-2}.

We used N^+ or O^+ ion implantation with the energy of 25 keV and dose of $2 \cdot 10^{17}$ cm^{-2}. The ion flux was of $3 \cdot 10^{12}$ ions$\cdot$cm$^{-2}\cdot$s. After implantation we used the furnace annealing in Ar ambient at the temperature of 1200^{o}C (1 hour).

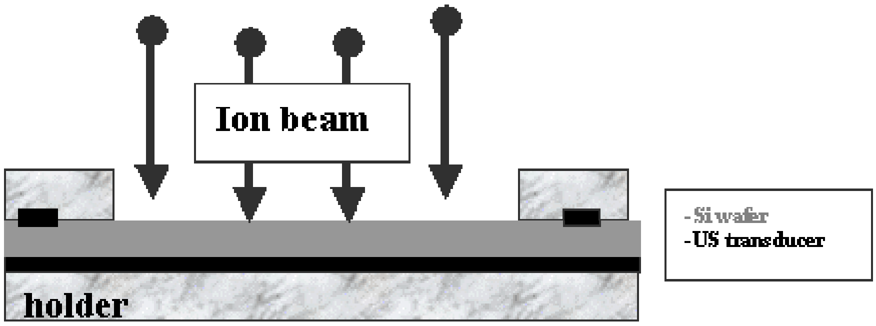

Figure 1. Schema of the cell for *in-situ* UST.

IR-transmission spectra have been measured within the range of 700 – 1400cm^{-1} using spectrometer IKS-25. Initial silicon wafer was used as a reference sample.

ToF-SIMS dopant profiling was performed with a ToF-SIMS IV system in the dual beam mode with 0.5 kV Cs^+ sputtering and 10 kV Ar^+ primary ion beam for secondary ion generation.

3. RESULTS AND DISCUSSION

IR spectra (Fig. 2a) had typical shape for the case of absorption by silicon-oxygen phase with two well pronounced bands (maximum positions at ~800 and ~ 1070 cm^{-1}), which are known to be connected with symmetrical and asymmetrical vibrations of oxygen atoms in Si-O-Si bridges, correspondingly.[6]

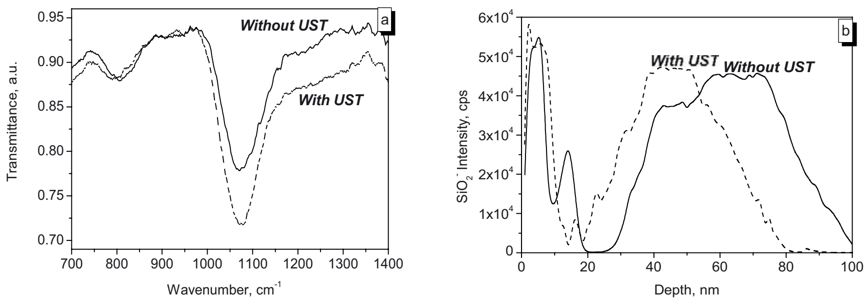

Figure 2. Influence of UST on SiO_2 phase formation after thermal annealing at 1200^o C, 1h.; a- IR spectra, b-ToF-SIMS depth profiles.

A long high-frequency tail on the spectral curves is also usual for this case, but was observed only for rather thick (more than 40 nm) oxide films.[7] These facts evident that implantation of the O^+ ions and subsequent annealing resulted in appearance of the buried layer of silicon-oxygen phase (SiO_x) in silicon wafer both in cases with and without US action.

At the same time, the peak position of the main absorption band for the samples treated with US (1078 cm^{-1}) is something (~7 cm^{-1}) shifted to high frequency range, if compare with US-untreated crystal, and integral absorbance for these samples is also higher (~20%). These facts should mean that US treatment leads to formation of layer with larger value of stoichiometry index *x*, which is close to 2.

Fig.2b shows the SIMS profiles for an implanted sample with and without UST after annealing. The US-untreated samples show a broad oxygen distribution, which is caused by a sub-stoichiometric SiO_2. The distribution separates into two peaks, one of which is at R_p = 65 nm, and other at the damage peak at R_p-ΔR_p = 50 nm. The oxygen distribution profile for the sample implanted with UST has one maximum in the range of R_p-ΔR_p ~ 45 nm. Oxygen concentration in a maximum is substantially higher then for the sample implanted without UST and corresponds to stoichiometrical one for the SiO_2 film of 15 nm thickness.

IR spectra of the nitrogen-implanted samples (Fig.3a) had some pronounced bands (peak positions were ~ 840, 905, 940 and near 1060 cm^{-1}), which are characteristic for absorption on Si-N and Si-O bonds. According to literature data [8,9] the 830 cm^{-1} band is connected with absorption on Si-N bonds in amorphous S_3N_4 films, the band 900 cm^{-1} characterizes Si-N bonds in amorphous SiO_xN_y films, whereas the band 935 cm^{-1} is the main absorption band in crystalline β-S_3N_4 phase.

For the samples untreated with US the band 940 cm^{-1} was rather weak, this fact means that in this case nitrogen implantation leads to formation of mainly amorphous silicon-nitrogen phase. If ion implantation was combined with US treatment this band markedly (1.5 times) increased, whereas the 940cm^{-1} band increased drastically (about order of magnitude). Hence, US action leads not only to growth of silicon-nitride buried layer, but this layer is to a high extent crystalline.

Absorption on Si-O vibrational mode changed due to US treatment, but the maximum position of the corresponding band changed remarkably (1070 cm^{-1} in comparison with 1055 cm^{-1} for US-untreated sample), and absorption decrease also takes place. It may be caused by the increase of the surface oxide thickness during annealing the samples, implanted without UST, whereas implantation with UST leads to the enrichment of the surface by nitrogen, and it blocks Si oxidation during annealing process.

Nitrogen distribution profiles for the samples with and without UST are shown in Fig 3b. One can see that UST leads to some shift of the distribution profile toward sample surface and to its narrowing. Nitrogen concentration increases in the sub-surface region in the samples implanted with the UST.

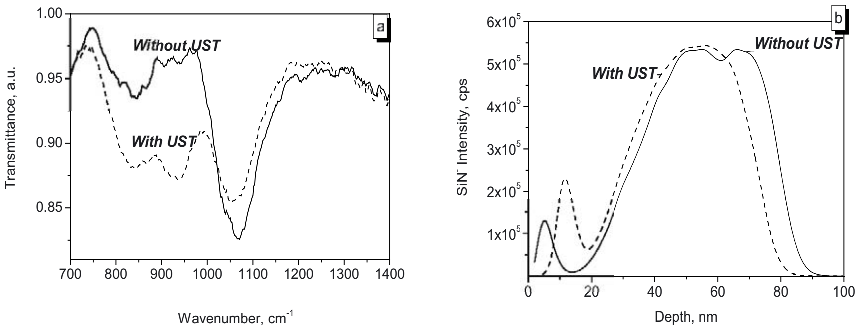

Figure 3. Influence of UST on Si_3N_4 phase formation after thermal annealing at 1200° C, 1h. a- IR spectra, b-ToF-SIMS depth profiles.

It is known that the kinetics of Si_3N_4 and SiO_2 dielectric phases is influenced by point defects. So, the presence of vacancies stimulates the SiO_2 phase precipitation and growth, whereas synthesis of a Si_3N_4 phase needs an excess concentration of interstitial atoms. We have shown[4] that the excitation of ultrasonic waves in a wafer during an implantation gives to spatial separation of the point defects. The interstitial silicon atoms under US wave action diffuse deep into the wafer, whereas the vacancies collect in complexes and remain in an area of an implantation. Such redistribution of the point defects does gives in the change of the buried layer formation kinetics in silicon.

4. CONCLUSIONS

It is shown that using the US treatment the ion-induced morphology near the R_p range can be manipulated to facilitate or promote the formation of higher quality buried layers, and gives the possibility to create super-thin stoicheometrical SiO_2 buried layers at doses $< 4 \cdot 10^{17}$ cm^{-2}.

ACKNOWLEDGEMENT

This work was partly supported by the STCU (Project #2367).

REFERENCES

1. A. Proßl et al., Silicon on insulator: materials aspects and applications, *Solid State Electron.*, **44**, 775-788 (2000).
2. S. Bagehi et al., Dose dependence of microstructural development of buried oxide in oxygen implanted SOI material, *Appl. Phys. Lett.,* **71**(15), 2136-2138 (1997).
3. O.W. Hollond et al., Formation of ultrathin, buried oxides in Si by O^+ ion implantation, *Appl. Phys. Lett*., **69**(5), 674-676 (1996).
4. B. Romanyuk et al., Modification of the Si amorphization process by in situ ultrasonic trestment during ion implantation, *Semicond. Sci. Technol*., **16**, 1-5 (2001).
5. S. Ostapenko et al., Change of minority carrier diffusion length in policrystalline silicon by ultrasound treatment, *Semicond. Sci. Technol.,* **10**, 1494-1500 (1995).
6. A. Lehmann et al., Optical phonons in amorphous silicon oxides. I. Calculation of the density of states and interpretation of LO-TO splittings of amorphous SiO_2, *Phys. Stat. Sol. (b),* **117**(2), 689-698 (1983).
7. I.P. Lisovskyy et al., IR spectroscopic investigation of SiO_2 film structure, *Thin Solid Films*. **213**, 164-169 (1992).
8. T.A. Kruse et al., Peculiarities of the IR absorption on Si-N bonds in silicon implanted by nitrogen, *Non-Organic Materials (in Russian)*, **26**(12), 2457-2460 (1990).
9. B.N. Romanjuk et al., Processes of formation of buried insulating layer in Si at implantation of N^+ and O^+ ions, *Ukr. Journ. Phys.* (*in Russian*), **37**(3), 389-394 (1992).