OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

Final Report
for
CRADA No. ORNL 98-499
with
Agere Systems, Inc.

Critical Vacancy-Driven Phenomena in High-Energy Ion-Implanted Silicon

UT-BATTELLE
ORNL-27 (4-00)

Project Title: Critical Vacancy-Driven Phenomena in High-Energy Ion-Implanted Silicon

ID: ORNL 98-499

PI: Tony E. Haynes, Solid State Division, Oak Ridge National Laboratory

Phone: (865) 576-2858

Partners: Agere Systems Inc., Murray Hill, NJ

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Background

High-energy (MeV) ion implantation is now being rapidly introduced into integrated circuit manufacturing because it promises process simplification and improved device performance. However, high-energy implantation introduces an imbalance of excess vacancies and vacancy-cluster defects in the near-surface region of a silicon crystal. These defects interact with dopants affecting diffusion and electrical activation during subsequent processing.

Research Objective

The objective of this project was to develop sufficient understanding of the physical mechanisms underlying the evolution of these defects and interactions with dopant atoms to enable accurate prediction and control of dopant diffusion and defect configurations during processing. This project supported the DOE mission in science and technology by extending ongoing Basic Energy Sciences programs in ion-solid physics and x-ray scattering at ORNL into new areas. It also strengthened the national capability for advanced processing of electronic materials, an enabling technology for DOE programs in energy conversion, use, and defense.

Results

A systematic method to generate large, controllable, and spatially-isolated vacancy concentrations in silicon was developed using high-energy implantation. This method permitted unprecedented flexibility and sensitivity in experiments designed to measure interactions involving vacancies and vacancy-clusters. The evolution of vacancy profiles during thermal treatments was monitored using two new methods developed by the CRADA team. These methods were:

(a) measurement of vacancy cluster depth-profiles by labeling the clusters with gold atoms, and

(b) measurement of x-ray diffuse scattering profiles in cross-section using a submicron x-ray beam at the Advanced Photon Source.

The list of CRADA accomplishments includes the following:

1. measurements of the number of excess vacancies produced per ion implanted as a function of ion mass and comparison of this number to simulation;
2. determination of the binding energy of vacancies to vacancy clusters in silicon;
3. enhanced electrical activation of certain dopants; and
4. observation of a new peak in the vacancy profile near the oxide-silicon interface following high-energy implantation into silicon-on-insulator substrates.

These findings were reported in journal publications and conference presentations. In addition, one patent filing resulted from finding C above. A complete list of publications follows below. Summary publications 1-4 listed below correspond respectively to each of the above accomplishments. Copies of these summary publications are included as attachments to this report.

DOCUMENTATION OF CRADA ACCOMPLISHMENTS

Patents (copy of cover page attached)

US Patent No. 6,632,728 – H.-J. L. Gossmann, T. E. Haynes, R. Kalyanaraman, L. Pelaz, C. S. Rafferty, and V. C. Venezia, "Increasing the electrical activation of ion-implanted dopants," assigned to CRADA Partner, Agere Systems Inc. (Allentown, PA); application filed July 16, 2001; patent issued October 14, 2003.

Summary Publications in Refereed Journals (copies attached)

1. R. Kalyanaraman, T. E. Haynes, V. C. Venezia, D. C. Jacobson, H.-J. Gossmann, and C. S. Rafferty, "Quantification of excess vacancy defects from high-energy ion implantation in Si by Au labeling," *Appl. Phys. Lett.* **76**, 3379 (2000).

2. R. Kalyanaraman, T. E. Haynes, O. W. Holland, H.-J. Gossmann, C. S. Rafferty, and G. H. Gilmer, "Binding energy of vacancies to clusters formed in Si by high-energy ion implantation," *Appl. Phys. Lett.* **79**,1983 (2001).

3. R. Kalyanaraman, V. C. Venezia, L. Pelaz, T. E. Haynes, H.-J. L. Gossmann, and C. S. Rafferty, "Enhanced low-temperature electrical activation of B in Si," *Appl. Phys. Lett.* **82**, 215 (2003).

4. R. Kalyanaraman, T. E. Haynes, O. W. Holland, and G. H. Gilmer, "Character of defects at an ion-irradiated buried thin-film interface," *J. Appl. Phys.* **91**, 6325 (2002).

Additional Publications (reprints available upon request)

Refereed Journal Articles

5. V. C. Venezia, D. J. Eaglesham, T. E. Haynes, A. Agarwal, D. C. Jacobson, H.-J. Gossmann, and F. H. Baumann, "Depth profiling of vacancy clusters in MeV-implanted Si using Au labeling," *Appl. Phys. Lett.* **73**, 2980 (1998).

6. V. C. Venezia, T. E. Haynes, A. Agarwal, L. Pelaz, H.-J. Gossmann, D. C. Jacobson, and D. J. Eaglesham, "Mechanism for the reduction of interstitial supersaturations in medium-energy ion-implanted silicon following MeV co-implantation," *App. Phys. Lett.* **74**, 1299 (1999).

7. M. Yoon, B. C. Larson, J. Z. Tischler, T. E. Haynes, J.-S. Chung, G. E. Ice, and P. Zschack, "Use of x-ray microbeams for cross-section depth profiling of MeV ion-implantation induced defect clusters in silicon," *Appl. Phys. Lett.* **75**, 2791 (1999).

8. V. C. Venezia, R. A. Brown, R. Kalyanaraman, T. E. Haynes, O. W. Holland, and J. S. Williams, "Comment on 'Interstitial-type defects away from the projected ion range in high-energy ion implanted and annealed silicon,' by Kogler, et al.", *Appl. Phys. Lett.* **77**, 151 (2000).

9. R. Kalyanaraman, T. E. Haynes, M. Yoon, B. C. Larson, D. C. Jacobson, H.-J. Gossmann, and C. S. Rafferty, "Quantitative evolution of vacancy-type defects in high-energy ion-implanted Si: Au labeling and the vacancy implanter," *Nucl. Instrum. Meth. B* **175-177**, 182-186 (2001).

10. V. C. Venezia, L. Pelaz, H.-J. Gossmann, T. E. Haynes, and C. S. Rafferty, "The binding energy of vacancy clusters generated by high-energy ion implantation and annealing in silicon," *Appl. Phys. Lett.* **79**, 1273 (2001).

11. V. C. Venezia, L. Pelaz, H.-J. L. Gossmann, A. Agarwal, and T. E. Haynes, "Radiation enhanced diffusion of Sb and B in silicon during implantation below 400°C," *Phys. Rev. B* **69**, 125215 (2004).

Conference Proceedings Articles

12. V.C. Venezia, D. J. Eaglesham, T. E. Haynes, Aditya Agarwal, D. C. Jacobson, H.-J. Gossmann, Thomas Friessnegg, and Bent Nielsen, "Vacancy supersaturations produced by high-energy ion implantation," p. 926 in Semiconductor Silicon 1998 (Electrochem. Soc. Proc. 98-1), edited by H. Huff, U. Gösele, and H. Tsuya (The Electrochemical Society, Pennington, NJ, 1998).

13. V. C. Venezia, T. E. Haynes, A. Agarwal, H.-J. Gossmann, L. Pelaz, D. C. Jacobson, D. J. Eaglesham, and J. L. Duggan,"Defects and diffusion in MeV-implanted silicon," p. 784 in Proc. 15th Int'l Conf. on Applic. of Accelerators in Research and Industry, edited by J. L. Duggan and I. V. Morgan (Am. Inst. Phys., New York, 1999).

14. M. Yoon, B. C. Larson, J. Z. Tischler, T. E. Haynes, J.-S. Chung, G. E. Ice, and P. Zschack, "Use of x-ray microbeams for depth-profiling of MeV ion-implantation induced defect clusters in silicon," pp. 175–186 in Proceedings of 1999 Advanced Study Institute on Exploration of subsurface phenomena by particle scattering held Oct. 19-23, 1998, Monterey, CA; ed. by N. Q. Lam, C. A. Melendres, & S. K. Sinha (Am. Inst. Phys., New York).

15. R. Kalyanaraman, T. E. Haynes, V. C. Venezia, D. C. Jacobson, H.-J. Gossmann, and C. S. Rafferty, "Calibration of the Au labeling technique to measure vacancy defects in silicon," p. B9.2.1 in Si Front-End Processing- Physics and Technology of Dopant-Defect Interactions II, edited by A. Agarwal, L. Pelaz, H.-H. Vuong, P. Packan, and M. Kase, Materials Research Society, Pittsburgh, PA (2000). [MRS Symp. Proc. 610, B9.2.1 (2000).]

16. R. Kalyanaraman, T. E. Haynes, D. C. Jacobson, H.-J. Gossmann, and C. S. Rafferty "Quantitative Profiles of Vacancy Cluster Defects Produced by MeV Ion Implantation in Si: Species and Dose Dependence," p. B9.4.1 in Si Front-End Processing- Physics and Technology of Dopant-Defect Interactions II, edited by A. Agarwal, L. Pelaz, H.-H. Vuong, P. Packan, and M. Kase, Materials Research Society, Pittsburgh, PA (2000). [MRS Symp. Proc. 610, B9.4.1 (2000).]