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CRADA Final Report for CRADA Number ORNL 94-0270

ION IMPLANTATION PROCESSING TECHNOLOGIES FOR TELECOMMUNICATIONS ELECTRONICS

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Ion Implantation Processing Technologies for Telecommunications Electronics

ORNL Principal Investigator: T. E. Haynes
Industrial Partner: Bell Laboratories, Lucent Technologies

The subject CRADA was a collaboration between Oak Ridge National Laboratory and Bell Laboratories, Lucent Technologies (formerly AT&T Bell Laboratories) to explore the development of ion implantation technologies for silicon integrated circuit (IC) manufacturing. This CRADA effort resulted in significant scientific contributions that have had, and will continue to have, substantial impact on the design of silicon IC manufacturing processes, both directly and indirectly. The direct impact has resulted from laboratory evaluation of ion implantation-based solutions to three key problems in IC manufacturing: dopant diffusion, metal contamination, and the availability of low-cost silicon-on-insulator (SOI) wafers. Without such solutions, enhanced diffusion of dopants would soon limit the density and speed of ICs while metal contamination would cause device failures and excess power consumption. In addition, the industry will soon require a large supply of low-cost SOI wafers to enable continued advances in speed, power efficiency, and reliability.

During this CRADA, the Laboratory and Partner conducted laboratory evaluations of ion implantation-based schemes for reducing enhanced diffusion of implanted dopants by the introduction of carbon, more effective removal (gettering) of metal contamination within IC chips by high-energy implantation, and a fourfold reduction of the implant dose needed for separation of SOI layers by co-implantation of He with H. All three of these solutions were demonstrated on the laboratory scale during the course of the CRADA. The CRADA partner is evaluating the first two schemes in a full-scale manufacturing environment. These two developments are summarized in the attached publications #1 (Stolk et al.) and #2 (Benton et al.). The SOI development, summarized in the attached publication #3 (Agarwal et al.), has the potential to significantly reduce the cost and increase the production rate of SOI wafers and is the subject of a pending patent application (Invention Disclosure #ERID-0274C). The economic payoff from these three developments is potentially very large and will be realized by the IC industry within two to five years.

In the latter stages of the CRADA, the team also investigated the basic mechanisms controlling enhanced diffusion of boron in silicon following ultralow-energy ion implantation. The industry trend is to use extremely low ion-implantation energies to create shallower doped layers that are necessary as the devices are made smaller. The outcome of these investigations is summarized in the attached publication #4 (Agarwal et al.). This work resulted in the demonstration that surface annihilation of excess interstitials reduces the diffusion enhancement caused by the interstitials to negligible levels as the implant energy approaches 1 keV and below. The CRADA team also made the initial discovery of an important new effect—boron-enhanced diffusion. This new effect becomes dominant over traditional transient-enhanced diffusion of boron as the implant energy is lowered (see attached publication 4). This discovery has stimulated a significant amount of continuing research by the Partner, as well as by others who are competitive in this field, in order to determine the underlying mechanism for this effect. It has also motivated a redirection of development efforts in the industry away from controlling damage to mitigating chemical reactions at large boron concentrations.

This CRADA will also have a significant indirect impact on IC manufacturing because of the development during the CRADA of sufficient quantitative understanding of enhanced-dopant diffusion and metal gettering to derive accurate physical models suitable for use in manufacturing simulators. As the complexity of IC technology increases, the costs and delays associated with actual manufacturing trials of new processes are becoming prohibitive and chip makers are increasingly relying on these simulators to design, test, and choose winning processes. Specific innovative insights developed during the CRADA include:

(1) quantitative determination of mechanisms of metal gettering by high-energy implantation;
(2) quantitative measurements of the amounts and types of implant damage that contribute to enhanced-dopant diffusion as functions of implant dose, energy, and dopant type;
(3) reduction of damage retention in large boron concentrations;
(4) experimental demonstration of the reduction of transient-enhanced diffusion with decreasing implant depth; and
(5) identification of a new mechanism of enhanced diffusion in ultrashallow profiles that arises from a chemical phase transformation instead of implant damage.

The CRADA partner has already incorporated physical models developed in this project into their simulator, and it is anticipated that other chip makers will soon do the same. The new understanding developed in this CRADA will thus enable these chip manufacturers to focus their process-development efforts more efficiently. This work has also refined the process window for 0.1-μm technology, due for production in 2005, thereby providing manufacturers of ion implanters the lead-time they will need to develop the specifications for their future product lines. The payoffs from these indirect contributions to manufacturing technology will be realized in 4–10 years.

This CRADA effort has been recognized by the semiconductor device community as demonstrated by invitations received by team members to give key invited talks (list attached), not only at major international conferences but also at more focused, device-oriented workshops. The presentation at the International Electronic Devices Meeting is particularly noteworthy in that this is a high-profile meeting focusing on leading-edge device technology that rejects approximately 80% of the submitted papers. Acceptance at this meeting is a clear indicator of recognized impact on device technology. In addition, results of this CRADA were highlighted in two of the leading semiconductor trade journals [A. Agarwal, cited in *Semiconductor International* **20** (4) p. 54 (April 1997); and *Solid State Technology* **40** (7), p. 78 (July 1997)], and the SOI development was recognized with the Best Paper Award at a 1997 SOI conference.

During the course of this CRADA, the ORNL PI (T. E. Haynes) spent approximately 150 days conducting experiments at Bell Laboratories. These intermittent visits provided a valuable opportunity to learn about other related areas of semiconductor processing technology and develop collaborations beyond the scope of this CRADA with other Bell Labs scientists that will continue for at least the next several years.

Documentation of CRADA Accomplishments
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Ion Implantation Processing Technologies for Telecommunications Electronics

Patents

Patent Pending: "Manufacture of Semiconductor Thin Films," application filed June 26, 1997, based on Invention Disclosure No. – Invention Disclosure, ERID-0274C.; Inventors– A. Agarwal (ORNL), T. E. Haynes (ORNL), O. W. Holland (ORNL), V. C. Venezia (ORNL), and D. J. Eaglesham (Lucent Technologies).

Summary Publications (copies attached)

1. P. A. Stolk, H.-J. Gossmann, D. J. Eaglesham, D. C. Jacobson, C. S. Rafferty, G. H. Gilmer, M. Jaraíz, J. M. Poate, and T. E. Haynes, "Physical Mechanisms of Transient Enhanced Dopant Diffusion in Ion-Implanted Silicon," *J. Appl. Phys.* **81**, 6031 (1997).
2. J. L. Benton, P. A. Stolk, D. J. Eaglesham, D. C. Jacobson, J.-Y. Chen, J. M. Poate, N. T. Ha, T. E. Haynes, and S. M. Myers, "Iron Gettering Mechanisms in Silicon," *J. Appl. Phys.* **80**, 3275 (1996).
3. A. Agarwal, T. E. Haynes, V. C. Venezia, O. W. Holland, and D. J. Eaglesham, "Efficient Production of Silicon-on-Insulator Films by Co-Implantation of He^+ with H^+," *Appl. Phys. Lett.* **72**, 1086 (1998).
4. A. Agarwal, H.-J. Gossmann, D. J. Eaglesham, L. Pelaz, S. B. Herner, D. C. Jacobson, T. E. Haynes, and R. Simonton, "Damage, Defects, and Diffusion from Ultra-Low-Energy (0-5 keV) Ion Implantation of Silicon," *Mat. Sci. Semicond. Proc.* **1**, 17 (1998).

Additional Publications (reprints available on request)

5. A. Agarwal, H.-J. Gossmann, D. J. Eaglesham, S. B. Herner, A. T. Fiory, and T. E. Haynes, "Boron-Enhanced Diffusion of Boron from Ultra-Low Energy Ion Implantation," *Appl. Phys. Lett.* **74**, 2435 (1999).
6. A. Agarwal, D. J. Eaglesham, H.-J. Gossmann, L. Pelaz, S. B. Herner, D. C. Jacobson, T. E. Haynes, and Yu. E. Erokhin, "Boron-Enhanced Diffusion of Boron from Ultralow-Energy Boron Implantation," p. 1232 in *Semiconductor Silicon 1998 (Electrochem. Soc. Proc. 98-1)*, ed. by H. Huff, U. Gösele, and H. Tsuya (The Electrochemical Society, Pennington, NJ, 1998).
7. A. Agarwal, H.-J. Gossmann, D. J. Eaglesham, L. Pelaz, D. C. Jacobson, J. M. Poate, and T. E. Haynes, "Critical Issues in Ion Implantation of Silicon Below 5 keV: Defects and Diffusion," *Materials Science and Engineering A– Structural Materials* **253** (1-2), 269(1998).

8. A. Agarwal, H.-J. Gossmann, D. C. Jacobson, D. J. Eaglesham, M. Sosnowski, J. M. Poate, I. Yamada, J. Matsuo, and T. E. Haynes, "Enhanced Diffusion From Decaborane Molecular Ion Implantation," *Appl. Phys. Lett.* **73**, 2015 (1998).
9. M. K. Weldon, M. Collot, Y. J. Chabal, V. C. Venezia, A. Agarwal, T. E. Haynes, D. J. Eaglesham, S. B. Christman, and E. E. Chaban, "The Mechanism of Silicon Exfoliation Induced by Hydrogen/Helium Co-Implantation," *Appl. Phys. Lett.* **73**, 3721 (1998).
10. A. Agarwal, D. J. Eaglesham, H.-J. Gossmann, L. Pelaz, S. B. Herner, D. C. Jacobson, T. E. Haynes, Yu. E. Erokhin, and R. Simonton, "Boron-Enhanced Diffusion of Boron: The Limiting Factor for Ultra-Shallow Junctions," *Intl. Electron. Dev. Mtg. Tech. Digest,* 467 (1997).
11. H.-J. Gossmann, T. E. Haynes, P. A. Stolk, C. A. King, R. W. Johnson, D. C. Jacobson, J. M. Poate, H. S. Luftman, T. Mogi, and M. O. Thompson, "The Interstitial Fraction of Diffusivity of Common Dopants in Silicon," *Appl. Phys. Lett.* **71**, 3862 (1997).
12. A. Agarwal, H.-J. Gossmann, D. J. Eaglesham, L. Pelaz, D. C. Jacobson, T. E. Haynes, J. Jackson, and Y. Erokhin, "Reduction of Transient Diffusion from 1–5 keV Si+ Ion Implantation due to Surface Annihilation of Interstitials," *Appl. Phys. Lett.* **71**, 3141 (1997).
13. Aditya Agarwal, H.-J. Gossmann, D. J. Eaglesham, D. C. Jacobson, T. E. Haynes, Yu. E. Erokhin, R. Simonton, and J. M. Poate, "0.5 to 5 keV Ion Implantation for Ultra-Shallow Junctions," *Proceedings of the Fourth International Workshop on the Measurement, Characterization, and Modeling of Ultra-shallow Doping Profiles in Semiconductors* (April 6–9, 1997, Research Triangle Park, NC).
14. D. J. Eaglesham, T. E. Haynes, H.-J. Gossmann, D. C. Jacobson, P. A. Stolk, and J. M. Poate, "Transient Enhanced Diffusion of Sb and B in Silicon due to MeV Silicon Implants," *Appl. Phys. Lett.* **70**, 3281 (1997).
15. A. Agarwal, T. E. Haynes, D. J. Eaglesham, H.-J. Gossmann, D. C. Jacobson, J. M. Poate, and Yu. E. Erokhin, "Interstitial Defects in Silicon from 1-5 keV Si^+ Ion Implantation," *Appl. Phys. Lett.* **70**, 3332 (1997).
16. T. E. Haynes, D. J. Eaglesham, P. A. Stolk, H.-J. Gossmann, D. C. Jacobson, and J. M. Poate, "Interactions of Ion Implantation Induced Interstitials with Boron at High Concentrations in Silicon," *Appl. Phys. Lett.* **69**, 1376 (1996).
17. D. J. Eaglesham, A. Agarwal, T. E. Haynes, H.-J. Gossmann, D. C. Jacobson, and J. M. Poate, "Damage and Defects from Low-Energy Implants in Si," *Nucl. Instrum. & Methods Phys. Res. Sect. B* **120**, 1 (1996).
18. J. L. Benton, P. A. Stolk, D. J. Eaglesham, D. C. Jacobson, J.-Y. Cheng, J. M. Poate, S. M. Myers, and T. E. Haynes, "The Mechanisms of Iron Gettering in Silicon by Boron Ion-Implantation," *J. Electrochem. Soc.* **143**, 1406 (1996).

19. D. J. Eaglesham, P. A. Stolk, J.-Y. Cheng, H.-J. Gossmann, T. E. Haynes, and J. M. Poate, "{311} Defects in Ion-Implanted Silicon: The Cause of Transient Diffusion and a Mechanism for Dislocation Formation," p. 451 in *Microscopy of Semiconducting Materials, 1995*, ed. by A. G. Cullis, A. E. Staton-Bevan, and J. L. Hutchison (Institute of Physics, Bristol, United Kingdom, 1996).
20. P. A. Stolk, J. L. Benton, D. J. Eaglesham, J.-Y. Cheng, J. M. Poate, S. M. Myers, and T. E. Haynes, "The Mechanism of Iron Gettering in Boron-Doped Silicon," *Appl. Phys. Lett.* **68**, 51 (1996).
21. D. J. Eaglesham, P. A. Stolk, H.-J. Gossman, T. E. Haynes, and J. M. Poate, "Implant Damage and Transient-Enhanced Diffusion in Si," *Nucl. Instr. and Methods Phys. Res. Sect. B* **106**, 191 (1995).

Invited Talks by ORNL Members of CRADA

22. A. Agarwal, "Modeling Enhanced Diffusion of Implanted Dopants Based on Physical Understanding of the Phenomena," *International Workshop on Challenges in Predictive Process Simulation* (August 1997, Wandlitz, Germany).
23. A. Agarwal, "New Aspects of Very Low Energy Ion Implantation for Ultrashallow Junctions," *1997 Spring Meeting of the Materials Research Society* (April 1997, San Francisco, CA).
24. A. Agarwal, "Damage, Defects, and Diffusion from Low-Energy Implantation in Silicon," *1997 Annual Meeting of the TMS* (February 1997, Orlando, FL).
25. T. E. Haynes, "Critical Issues in Ion Implantation of Silicon Below 5 keV," *1997 Engineering Foundation Conference on Ion Beam Modification of Ceramics and Semiconductors* (May 1997, Barga, Italy).
26. T. E. Haynes, "Defects and Diffusion in Ultrashallow Ion Implantation of Silicon," *1997 Meeting of the Greater Southwest Implant Users' Group* (October 1997, Denton, TX).

Additional Significant Talks by ORNL Members of CRADA

27. A. Agarwal, "Boron-Enhanced Diffusion of Boron: The Limiting Factor for Ultra-Shallow Junctions," *1997 International Electron Devices Meeting* (December 1997, Washington, DC).
28. A. Agarwal, "0.5 to 5 keV Ion Implantation for Ultrashallow Junctions," *4th Int'l Workshop on Measurement, Characterization, and Modeling of Ultra-Shallow Doping Profiles in Semiconductors* (April 1997, Research Triangle Park, NC).
29. A. Agarwal, "Mechanism of Silicon Exfoliation by Hydrogen Implantation or Hydrogen/Helium Co-Implantation," *1997 IEEE Int'l Silicon-on-Insulator Conference* (October 1997, Fish Camp, CA).