

Springer Series in
MATERIALS SCIENCE

Editors: R. Hull C. Jagadish R.M. Osgood, Jr. J. Parisi Z. Wang

The Springer Series in Materials Science covers the complete spectrum of materials physics, including fundamental principles, physical properties, materials theory and design. Recognizing the increasing importance of materials science in future device technologies, the book titles in this series reflect the state-of-the-art in understanding and controlling the structure and properties of all important classes of materials.

Please view available titles in *Springer Series in Materials Science*
on series homepage <http://www.springer.com/series/856>

Swift Heavy Ions for Materials Engineering and Nanostructuring

D.K. Avasthi

G.K. Mehta

Inter University Accelerator Centre

New Delhi

India



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

ISSN 0933-033X
ISBN 978-94-007-1228-7 (HB)
ISBN 978-94-007-1229-4 (e-book)

Copublished by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands with
Capital Publishing Company, New Delhi, India.

Sold and distributed in North, Central and South America by Springer, 233
Spring Street, New York 10013, USA.

In all other countries, except SAARC countries—Bangladesh, Bhutan, India, Maldives, Nepal,
Pakistan and Sri Lanka—sold and distributed by Springer, Haberstrasse 7,
D-69126 Heidelberg, Germany

In SAARC countries—Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan
and Sri Lanka—sold and distributed by Capital Publishing Company, 7/28, Mahaveer Street,
Ansari Road, Daryaganj, New Delhi, 110 002, India.

www.springer.com

Printed on acid-free paper

All Rights Reserved
© 2011 Capital Publishing Company

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 India.

Preface

Ion beams have been of increasing focus in fundamental and applied research in materials science. Development of ion beam facilities along with sophisticated devices for the characterization and analysis on nano scale has given a new direction in nanotechnology and towards tailoring desired properties in materials for their applications in various fields. A large amount of interesting research work in the direction of engineering materials properties with high energy heavy ion beams has been performed. Need was felt to have an overview of the work done in this direction by using high energy heavy ions [Swift Heavy Ions (SHI)].

The prime purpose of the book is to bring out salient features of research in materials with swift heavy ions. It will be of interest to young scholars engaged in research with swift heavy ions to focus towards specific problems in this emerging area. It has evolved from the experience gained by interacting with the large community of young researchers from various universities and research institutions in India and abroad. It was felt that because it is a relatively new area of research which is providing avenues of exploration in various directions, there is possibility of missing the directions required to focus on the emerging challenges in various areas, and that request from them for their contribution for this book may help in focussing their attention towards focussed goals. A consolidated compilation of contributions from the users of the high energy heavy ions for materials studies is being attempted here.

Swift heavy ions have a unique feature of depositing a large energy density in materials which can drive the material far from equilibrium, resulting in modifications in materials, difficult to achieve by other means. Studies on understanding of the modifications produced by swift heavy ions give an insight to the interaction of energetic ions with materials. The irradiation of materials by swift heavy ions can result in different effects in materials such as defect annealing, defect creation, ion track formation, plastic deformation etc. and these can be tuned by ion beam parameters. High energy density provided by SHI in laboratory allows to simulate extreme conditions.

Ion beams have been used for a long time to characterize the materials with techniques developed specifically for the situations which could not be handled with the conventional techniques. The worry that the ion beams being used to characterize the samples will damage the material soon turned into a challenge that the modifications in the properties during irradiation can be monitored in dynamic mode which can provide possibility of controlled change in the properties of the materials. This started the discipline of “Materials Engineering with Ion Beams”. It has now emerged as an area with immense scope of development particularly because of the way it is becoming possible to create ion beams with specific and diverse characteristics giving rise to new avenues to exploit. Considering the fact that the low energy ions have been in the field for a long time it was decided to concentrate on the high energy heavy ions.

This book is an effort to present a scenario of research in materials science with SHI in a way which could be useful for the students planning research in ion accelerator based materials science. We would like to emphasize that the material is prepared with the help of researchers in this area and is based on their publications and existing materials. The challenge was to try and convert the large number of research publications in the field into a kind of a text to motivate the students to plan their experiments with a focus on engineering some well defined property of some materials to make its application possible.

First three chapters provide an overview of the field, challenges in materials and state-of-the-art developments in ion beams, very brief description of ion matter interaction and survey of the wide field of applications of ion beams for the characterization and analysis of materials. The next two chapters are on the SHI induced ion beam mixing and SHI for synthesis and modification of nanostructured materials. The last chapter focusses on engineering the properties of materials with SHI, where various types of materials are considered. It covers different types of materials. It has not been possible to cover all the materials which have been worked upon using SHI irradiation.

This exposition of experimental work owes much to the persons who provided the information about the importance of ion beam interaction in changing the properties of materials in unique ways. We had significant inputs from the present and past research scholars who had been at IUAC for their PhD. We gratefully acknowledge Amit Kumar (now at LPMS, Toulouse, France), Y.K. Mishra (now at Kiel University, Germany), S.K. Srivastava (now faculty in IIT Kharagpur), S. Ghosh and Rajendra Singh (now faculty in IIT Delhi), D.C. Agarwal, R. Singhal and Yogita Batra. There are many to acknowledge but special role was played by Drs Naresh C. Mishra, Ajay Gupta, K.M. Varier, Anand Pathak, R.G. Sharma, Ashok Kumar, A.C. Chaudury, Ratnamala Chatterjee, S. Dhamodaran, Avinash Pandey, Utpal Joshi, T. Som, D. Behera, D. Mohanta and Maulik Patel, to name a few. The manuscript could only be completed because of the support from the colleagues in the Nuclear Science Centre [now Inter University Accelerator Centre—IUAC] who have

been active collaborators with the users from various institutions in experiments conducted with the Pelletron accelerator in New Delhi. The discussions at various occasions with scientists at IUAC e.g. D. Kanjilal, A. Tripathi, S. Chopra, Ravi Kumar, D. Kabiraj, Fouran Singh, K. Asokan, S. Mookherjee, S.A. Khan, P. Kulriya and I. Sulania had been fruitful.

The authors acknowledge the help rendered by Ms. Srashti Gupta and Mr. Jai Prakash in this project.

Appreciation, constant interest and encouragement by Dr. Amit Roy, Director IUAC, needs special mention. The financial assistance provided by the Department of Science & Technology and the help from the staff of the Inter University Accelerator Centre is gratefully acknowledged. In the end we would like to mention that it was late Dr. C.P. Srivastava of DST who gave the required push to take up this project.

February 2011

D.K. Avasthi
G.K. Mehta

Contents

<i>Preface</i>	v
1. Ion Beams for Materials Engineering—An Overview	1
1.1 Introduction	1
1.2 Challenges in Materials Science and Engineering	5
1.3 Ion Beam Based/Assisted Processes	12
1.4 Materials Modifications with Ion Beams	19
1.5 Possibilities of Tailoring the Materials Properties with Ion Beams	22
1.6 Why Ion Beams for Materials Engineering?	24
1.7 Specially Configured Ion Beams	25
1.8 Ion Beam Assisted Self Organization	34
1.9 Summary and Perspective	38
2. Ion Matter Interaction	47
2.1 Introduction	47
2.2 Nuclear and Electronic Energy Loss in Materials	48
2.3 Consequence of Large Electronic Energy Density Deposition by Swift Heavy Ions	54
2.4 Cooperative Effects of Nuclear and Electronic Energy Losses	57
2.5 Simulation Efforts to Understand Ion Irradiation Induced Modifications	62
2.6 Perspectives of Ion-Solid Interaction	63
2.7 Summary	64
3. Ion Beam Analysis	67
3.1 Introduction	67
3.2 Proton Induced X-ray Emission (PIXE)	69
3.3 Particle Induced γ -ray Emission (PIGE)	71

3.4	Ionoluminescence (IL)	71
3.5	Rutherford Backscattering Spectrometry (RBS)	71
3.6	RBS Channelling	74
3.7	Elastic Recoil Detection Analysis (ERDA)	75
3.8	Medium Energy Ion Scattering (MEIS)	79
3.9	Low Energy Ion Scattering (LEIS)	79
3.10	Nuclear Reaction Analysis (NRA)	79
3.11	Charged Particle Activation Analysis (CPAA)	80
3.12	Accelerator Mass Spectrometry (AMS)	81
3.13	Summary	82
4.	Engineering of Materials by Swift Heavy Ion Beam Mixing	86
4.1	Introduction	86
4.2	SHI Induced Mixing for Material Engineering	89
4.3	Interface Modification in Thermo-dynamically Immiscible Systems	101
4.4	Metal/Insulator, Semiconductor/Insulator and Insulator/Insulator Systems	102
4.5	Conclusions and Future Prospects	103
5.	SHI for Synthesis and Modifications of Nanostructured Materials	109
5.1	Introduction	109
5.2	Synthesis of Nanostructured Materials under Electronic Excitation	112
5.3	Nanostructures within Ion Track and at the Surface by Self-organization	116
5.4	Modification of the Metal-dielectric Nanocomposite Films	121
5.5	Tailoring the Mechanical Properties of Si Nanorod Structures	135
5.6	Summary	136
6.	Materials Engineering with Swift Heavy Ions	142
6.1	Carbon	143
6.2	Polymers	152
6.3	Semiconductors	164
6.4	Transparent Conducting Oxides (TCO)	171
6.5	Transition Metal Oxides (TMO)	176
6.6	Diluted Magnetic Semiconductors (DMS) and Other Magnetic Materials	181
6.7	High Temperature Superconductors (HTSC)	185
6.8	Special Oxides (Ferrites, Multiferroics and LCMO)	193
6.9	Resistive Random Access Memory (RRAM) Devices Based on Oxides	194

6.10 Quasicrystals	197
6.11 Alkali Halides	199
6.12 Plasmonic Materials	201
6.13 Materials for Energy	205
6.14 Nuclear Materials	209
6.15 Summary	211
<i>Appendix 1: Epitaxial Crystallization</i>	231
<i>Appendix 2: Sputtering</i>	235
<i>Appendix 3: Applications of the PIXE Technique</i>	246
<i>Appendix 4: Applications of RBS and ERDA</i>	255
<i>Index</i>	277