

# Bioactive Glasses and Glass-Ceramics



Fundamentals and Applications

Edited by:  
Francesco Baino  
Saeid Kargozar

The  
American  
Ceramic  
Society



WILEY



## Bioactive Glasses and Glass-Ceramics



# Bioactive Glasses and Glass-Ceramics

Fundamentals and Applications

*Edited by*

*Francesco Baino and Saeid Kargozar*



**WILEY**

Copyright © 2022 by The American Ceramic Society. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

The right of Francesco Baino and Saeid Kargozar to be identified as the authors of the editorial material in this work has been asserted in accordance with law.

*Registered Office*

John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

*Editorial Office*

111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at [www.wiley.com](http://www.wiley.com).

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

*Limit of Liability/Disclaimer of Warranty*

In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

*Library of Congress Cataloging-in-Publication Data*

Names: Baino, Francesco, editor. | Kargozar, Saeid, editor.

Title: Bioactive glasses and glass-ceramics : fundamentals and applications  
/ edited by Francesco Baino, Saeid Kargozar.

Description: Hoboken, New Jersey : Wiley-American Ceramic Society, [2022] |  
Includes bibliographical references and index.

Identifiers: LCCN 2022009994 (print) | LCCN 2022009995 (ebook) | ISBN  
9781119724513 (cloth) | ISBN 9781119724889 (adobe pdf) | ISBN  
9781119724667 (epub)

Subjects: LCSH: Bioactive glasses. | Glass-ceramics. | Glass in medicine. |  
Bioactive glasses—Therapeutic use. | Glass-ceramics—Therapeutic use.

Classification: LCC R857.G55 B544 2022 (print) | LCC R857.G55 (ebook) |  
DDC 610.28/4—dc23/eng/20220329

LC record available at <https://lcn.loc.gov/2022009994>

LC ebook record available at <https://lcn.loc.gov/2022009995>

Cover image: Courtesy Francesco Baino and Elisa Fiume

Cover design by Wiley

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

## Contents

**Preface** *xvii*

**List of Contributors** *xix*

- 1 Glass Crystallization and Glass-Ceramics – An Overview** *1*  
*Araceli de Pablos Martín and Delia S. Brauer*
  - 1.1 Introduction *1*
  - 1.2 Controlled Crystallization of Glasses *3*
  - 1.3 Nucleation *4*
  - 1.4 Crystal Growth *8*
  - 1.5 Conclusion *10*
  - References *10*
  
- 2 Crystallization of Glasses and Its Impact on Bioactivity and Other Properties** *17*  
*Araceli de Pablos Martín and Delia S. Brauer*
  - 2.1 Bioactive Glasses *17*
  - 2.2 Bioactive Glass-Ceramics *18*
  - 2.3 Influence of Crystallization on Processing *18*
  - 2.4 Influence of Crystallization on Mechanical Properties *20*
  - 2.5 Influence of Crystallization on Bioactivity *21*
  - 2.6 Conclusions and Perspectives *26*
  - References *27*
  
- 3 Bioactive Glass S53P4 – From a Statistically Suggested Composition to Clinical Success** *33*  
*Leena Hupa and Nina C. Lindfors*
  - 3.1 Background *33*
    - 3.1.1 Discovery of the Concept of Bioactive Glass and 45S5 Composition *33*
    - 3.1.2 Development of Bioactive Glasses in Finland *34*
    - 3.1.3 Bioactive Glass S53P4 Today *34*

3.2	Bioactive Glass S53P4 – From a Concept to First Clinical Trials	35
3.2.1	The First Series of Glasses, Including S53P4	35
3.2.2	Phenomenological Model of Bone Bonding	35
3.2.3	<i>In Vivo</i> Bone Bonding vs. Glasses with Al <sub>2</sub> O <sub>3</sub> and P <sub>2</sub> O <sub>5</sub>	36
3.2.4	Soft and Hard Tissue Bonding <i>In Vivo</i>	37
3.2.5	<i>In Vivo</i> Evidence of S53P4 in Bone Healing	37
3.2.6	Stimulatory Effect of S53P4 on Bone Healing	39
3.2.7	Antibacterial Effect of S53P4 <i>In Vitro</i>	39
3.3	Clinical Trials for the Development of Commercial Products	40
3.3.1	Glass Granules and Plates in the Oral and Maxillofacial Area	40
3.3.2	S53P4 Granules in Orthopedics	41
3.3.3	Clinical Use of S53P4 in the Treatment of Bone Infections	43
3.3.4	S53P4 in Fiber-Reinforced Calvarial Implants	44
3.4	Commercial Products	46
3.5	Research for New Compositions and Applications	47
3.5.1	Compositions Derived from S53P4	47
3.5.2	<i>In Vitro</i> Ion Release and Cell Culture Studies	48
3.5.3	Porous S53P4 Scaffolds in Weight-Bearing Applications	49
3.5.4	Putty-Like S53P4 Bone Filler	50
3.5.5	Recent Clinical Outcomes	51
3.6	Summary and Future Trends	52
	References	52

#### **4 Melt-Derived Bioactive Glasses: Beyond Silicate Glasses** 61

*Jonathan Massera*

4.1	Introduction	61
4.2	Silicate Bioactive Glasses	62
4.2.1	Silicate Glass for Bone Tissue Engineering	65
4.3	Phosphate Bioactive Glasses	67
4.3.1	Structure/Dissolution	67
4.3.2	Phosphate Glass for Bone Tissue Engineering	69
4.4	Phosphate Glass Fibers	70
4.5	Borate, Borosilicate, and Borophosphate Bioactive Glasses	71
4.5.1	Structure/Dissolution	71
4.5.2	Borate Glass for Tissue Engineering	73
4.6	Conclusion	73
	References	74

#### **5 Borate Bioactive Glass** 79

*Seiji Yamaguchi*

5.1	Introduction	79
5.2	Composition and Fabrication Process	79
5.3	Biological Reaction of Boron	81
5.4	Hard Tissue Regeneration	82
5.5	Soft Tissue Regeneration	82
5.6	Summary	84
	References	84

<b>6</b>	<b>Fabrication of Bioactive Structures from Sol–Gel Derived Bioactive Glass</b>	<b>87</b>
	<i>Durgalakshmi Dhinasekaran and Anuj Kumar</i>	
	List of Abbreviations	87
6.1	Regenerative Glasses – An Introduction	88
6.2	Glass Network and Bioactivity	89
6.3	Sol–Gel Process of Synthesizing Bioactive Glass Structures	93
6.4	Scaffold Structuring from Bioactive Glass	96
6.4.1	Foam Replication Method	97
6.4.2	Hydrogel Method	98
6.4.3	Electrospinning Method	104
6.4.4	3D Printing Method	106
6.5	Conclusion	111
	Acknowledgment	111
	References	111
<b>7</b>	<b>Processing of Bioactive Glass Scaffolds for Bone Tissue Engineering</b>	<b>119</b>
	<i>Elisa Fiume, Carla Migneco, Saeid Kargozar, Enrica Verné, and Francesco Baino</i>	
7.1	Introduction	119
7.2	Critical Issues and Challenges Related to Bioactive Glass Scaffolds	121
7.3	Fabrication Techniques	123
7.3.1	Foaming Methods	123
7.3.1.1	Gel-Cast Foaming	124
7.3.1.2	Sol–Gel Foaming	125
7.3.1.3	Thermal Decomposition of Chemical Compounds	125
7.3.2	Thermal Consolidation of Particles	126
7.3.2.1	Scaffold Manufacturing by the Use of Porogen Particles	126
7.3.2.2	Scaffold Manufacturing Without the Use of Porogen Particles	127
7.3.3	Freeze-Drying	128
7.3.3.1	Freeze-Casting of Suspensions	128
7.3.3.2	Ice-Segregation-Induced Self-Assembly Combined with the Sol–Gel Method	128
7.3.4	Foam Replica Method	128
7.3.5	Solid Freeform Fabrication	130
7.3.5.1	Selective Laser Sintering	130
7.3.5.2	Stereolithography	132
7.3.5.3	Fused Deposition Modeling	133
7.3.5.4	Ink-Jet Printing	134
7.3.5.5	Three-Dimensional Printing	135
7.3.5.6	Robocasting	136
7.4	Beyond Bone Tissue Engineering Through Using BG-Based Scaffolds	138
7.4.1	Hierarchical MBG-Based Scaffolds as Drug Release Platforms for <i>In Situ</i> Therapy	138
7.4.2	Multilayer Scaffolds for Interfacial Tissue Engineering	138
7.5	Conclusion	139
	References	140

<b>8</b>	<b>Strong, Tough Bioactive Glasses and Composite Scaffolds</b>	<b>147</b>
	<i>Qiang Fu</i>	
8.1	Introduction	147
8.2	Glass Composition	151
8.3	Fabrication Methods	151
8.3.1	Sol–Gel Processing	152
8.3.2	Thermal Bonding of Particles or Fibers	152
8.3.3	Polymer Foam Replication	152
8.3.4	Freeze Casting of Suspensions	154
8.3.5	Solid Freeform Fabrication	154
8.4	Mechanical Properties	155
8.4.1	Strength	155
8.4.2	Fatigue Resistance	157
8.4.3	Fracture Toughness and Reliability	158
8.4.4	Toughening of Bioactive Glass	159
8.5	Conclusions and Future Trends	162
	References	162
<b>9</b>	<b>Nano-bioactive Glass: Advances and Applications</b>	<b>173</b>
	<i>Ahmed El-Fiqi</i>	
9.1	Introduction	173
9.2	Bioactive Glass Nanoparticles	174
9.2.1	Synthesis Approaches	174
9.2.1.1	Sol–Gel Synthesis	175
9.2.1.2	Modified Sol–Gel Synthesis	175
9.2.1.3	Ultrasonic-Coupled Sol–Gel Synthesis	176
9.2.1.4	Modified Stöber Synthesis	177
9.3	Compositions of Sol–Gel BGn	177
9.4	Nanoscale Properties of Sol–Gel BGn	179
9.5	Biomedical Applications of BGn	180
9.6	Conclusion	189
	References	189
<b>10</b>	<b>Tailoring the Osteogenic Properties of Bioactive Glasses by Incorporation of Therapeutic Ions for Orthopedic Applications</b>	<b>203</b>
	<i>Sebastian Wilkesmann and Fabian Westhauser</i>	
10.1	Introduction	203
10.2	Ions Derived from Common Silicate-Based BGs	205
10.2.1	Calcium (Ca)	205
10.2.2	Silicon (Si)	205
10.2.3	Phosphorus (P)	206
10.3	Ions Derived from BGs Supplemented with Further Therapeutically Active Ions	207
10.3.1	Boron (B)	207
10.3.2	Cerium (Ce)	208
10.3.3	Cobalt (Co)	208
10.3.4	Copper (Cu)	209
10.3.5	Fluoride (F)	209

- 10.3.6 Gallium (Ga) 210
- 10.3.7 Iron (Fe) 210
- 10.3.8 Lithium (Li) 211
- 10.3.9 Magnesium (Mg) 211
- 10.3.10 Manganese (Mn) 212
- 10.3.11 Niobium (Nb) 212
- 10.3.12 Silver (Ag) 213
- 10.3.13 Strontium (Sr) 213
- 10.3.14 Zinc (Zn) 214
- 10.4 Summary and Conclusions 215
- References 217

## **11 Bioactive Glasses as Carriers for the Controlled Release of Therapeutic Species 227**

*Min Zhu and Yufang Zhu*

- 11.1 Introduction: From BG Themselves to Platform Materials 227
- 11.2 Therapeutic Ion Release 229
  - 11.2.1 Bioactive Ion Delivery 230
    - 11.2.1.1 Ionic Antibacterial Effects 230
    - 11.2.1.2 Ionic Pro-osteogenesis Effects 232
    - 11.2.1.3 Ionic Pro-angiogenesis Effects 233
    - 11.2.1.4 Ionic Anticancer Effects 234
  - 11.2.2 Control of the Ion Release Profiles 235
    - 11.2.2.1 Ion Solubility 236
    - 11.2.2.2 Crystallinity 237
    - 11.2.2.3 Specific Surface Area 237
    - 11.2.2.4 Medium Condition 237
- 11.3 Drug Release 238
  - 11.3.1 Antibacterial Drugs 241
  - 11.3.2 Small Therapeutic Drugs for Diseases 243
- 11.4 Biomolecule Release 245
- 11.5 Dual/Multi-species Release 246
- 11.6 Release Modulation on MBG-Based Carriers 247
  - 11.6.1 Pore Size 249
  - 11.6.2 Pore Structure 249
  - 11.6.3 Compositions 250
  - 11.6.4 Surface Modification 251
- 11.7 Conclusions and Perspectives 251
- References 252

## **12 Enhancing the Biological Performance of Bioactive Glasses by Combination with Phytotherapeutic Compounds 263**

*Kanwal Ilyas and Aldo R. Boccaccini*

- 12.1 Introduction 263
- 12.2 Phytotherapeutics: An Overview 264
- 12.3 Bioactive Glasses and Drug Delivery 272

- 12.4 Tailoring the Biological Response of Bioactive Glasses by the Interaction with Phytotherapeutics 273
  - 12.4.1 Bioactivity and Antimicrobial Tuning 273
  - 12.4.2 Biocompatibility and Cell Proliferation 276
  - 12.4.3 Sustained Release Kinetics of BGs Loaded with Phytotherapeutics 276
- 12.5 Loading Techniques of Phytotherapeutic Compounds on Bioactive Glasses 277
  - 12.5.1 Surface Modification of BGs 277
  - 12.5.2 Physicochemical Method 279
- 12.6 Bioactive Glass with Phytotherapeutics: Toward Therapeutic Applications 281
  - 12.6.1 Bone Tissue Engineering 281
  - 12.6.2 Wound Healing 281
  - 12.6.3 Anticancer and Cardiovascular Tissue Engineering 282
- 12.7 Summary and Outlook 283
  - References 283

### **13 Bioactive Glass-Based Coatings: Concepts for Improving the Biocompatibility of Implantable Materials 293**

*Jessica Fletcher, William Alles, Timothy James Keenan, and Anthony William Wren*

- 13.1 Introduction 293
  - 13.1.1 Current Concepts in Coating Technology 294
  - 13.1.2 Bioactive Glasses – Therapeutic Value as a Coating Material 297
- 13.2 Bioactive Glass Synthesis 298
- 13.3 Principles of Coating Processing 298
- 13.4 Characterization of Modified Surfaces 302
- 13.5 Composite Coatings: Diversity of Inorganic–Organic Hybrids 304
- 13.6 Conclusion 306
  - References 306

### **14 Laser Cladding and Laser Direct Glass Deposition of Bioactive Glass and Glass-Ceramics 311**

*Rafael Comesaña, Jesús del Val, Félix Quintero, Antonio Riveiro, Felipe Arias-González, Mohamed Boutinguiza, Fernando Lusquiños, and Juan Pou*

- 14.1 Laser Cladding and Laser Direct Glass Deposition 311
  - 14.1.1 The Laser Cladding (LC) Technique 311
  - 14.1.2 The Laser Direct Glass Deposition Technique (LDGD) 312
    - 14.1.3 Laser–Material Interaction 313
    - 14.1.4 The LC and LDGD Processing Station 314
      - 14.1.4.1 Laser Energy Sources and Optical Guidance 316
      - 14.1.4.2 Precursor Material Feeder and Powder Injectors 317
      - 14.1.4.3 Moving Devices, Process Control, and Monitoring System 319
  - 14.2 Bioactive Glasses for Laser Cladding Processes 320
    - 14.2.1 Glass Working Range 321
    - 14.2.2 Particle Size, Apparent Density, and Morphology 322
    - 14.2.3 Preplaced BG Powder 323
  - 14.3 Bioactive Glass and Glass-Ceramic Coatings by Laser Cladding 324
    - 14.3.1 Glass Structural Changes Induced by the Laser Cladding Process 324
    - 14.3.2 Substrate-Coating Bonding Mechanism 327

- 14.3.3 Bioactivity and Biocompatibility 328
- 14.4 Additive Manufacturing of Bioactive Glass by Laser Direct Deposition 329
  - 14.4.1 Influence of Processing Parameters in LDGD 330
  - 14.4.2 Cooling Rates, Bioactive Glass Structural Changes, and Mechanical Properties 331
  - 14.4.3 Bioactivity and Biocompatibility 333
- 14.5 Conclusions 336
  - Acknowledgments 336
  - References 336
  
- 15 Laser-Assisted Processing of  $\text{CaSiO}_3\text{-Ca}_3(\text{PO}_4)_2$  Bioactive Eutectic Glasses and Glass-Ceramics for Functional Applications 341**
  - Daniel J. Sola*
  - 15.1 Introduction: Bioactive Glasses and Glass-Ceramics 341
  - 15.2 Fundamentals of the Laser Floating Zone Technique 344
  - 15.3 Fabrication and Characterization of Rare-Earth-Doped  $\text{CaSiO}_3\text{-Ca}_3(\text{PO}_4)_2$  Biocompatible and Bioactive Eutectic Glasses and Glass-Ceramics 348
  - 15.4 Laser-Induced Breakdown Spectroscopy (LIBS) as a Complementary Analytical Tool for Monitoring the Formation of Hydroxyapatite Porous Layers 356
  - 15.5 Laser Machining and *In Vitro* Assessment of  $\text{CaSiO}_3\text{-Ca}_3(\text{PO}_4)_2$  Biocompatible and Bioactive Eutectic Glasses and Glass-Ceramics 360
  - 15.6 Fabrication of Buried Waveguides in  $\text{CaSiO}_3\text{-Ca}_3(\text{PO}_4)_2$  Bioactive Eutectic Glasses by Femtosecond Direct Laser Writing 363
  - 15.7 Conclusions and Outlook 366
    - Acknowledgments 367
    - References 367
  
- 16 Molecular Dynamics (MD) Simulations of Bioactive Glasses and Glass-Ceramics 375**
  - Maziar Montazerian, Collin Wilkinson, and John C. Mauro*
  - 16.1 Introduction 375
  - 16.2 Molecular Dynamics (MD) Simulations 376
    - 16.2.1 Structure of BGs 377
    - 16.2.2 Chemical Degradation of BGs 380
    - 16.2.3 Diffusion in BGs 383
    - 16.2.4 MD Simulation of Nano-BGs 385
    - 16.2.5 Crystallization of BGs 385
  - 16.3 Conclusion 388
    - Acknowledgment 389
    - References 389
  
- 17 *In Vitro* and *In Vivo* Studies of Bioactive Glasses 397**
  - Sadaf Batool, Zakir Hussain, and Usman Liaqat*
  - 17.1 Introduction 397
  - 17.2 Bioactive Glass 398
  - 17.3 Chemical Composition of Bioactive Glass 398
  - 17.4 Key Concepts Before Using Bioactive Glass for Tissue Regeneration 399
  - 17.5 Reactions of BGs in Physiological Fluids 401

- 17.6 Interaction of Bioactive Glass with Proteins 403
- 17.7 Cell Cycle Involved in Tissue Regeneration 404
- 17.8 *In Vitro/In Vivo* Evaluation of Bioactive Glass for Bone Tissue Regeneration 408
- 17.9 A Comparative Analysis of Silicate- and Borate-Based Glasses in Bone Tissue Regeneration 411
- 17.10 Bioactive Glass for Dentin Regeneration 412
- 17.11 Bioactive Glass for Cartilage Regeneration 413
- 17.12 Evaluation of Bioactivity in Cartilage Regeneration 415
- 17.13 Regeneration of Soft Connective Tissues 416
- 17.14 Bioactive Glass for Skin Tissue Regeneration 417
- 17.15 Bioactive Glass for Angiogenesis 417
- 17.16 Role of Other Metal-Based Network Modifiers in Tissue Regeneration (*In Vivo/In Vitro* Study) 419
- 17.17 List of FDA Approved Bioactive Glass 422  
References 423

## 18 Production of Bioactive Glass-Ceramics for Dental Application Through Devitrification of Glasses in the $\text{Na}_2\text{O}/\text{K}_2\text{O}-\text{CaO}-\text{MgO}-\text{SiO}_2-\text{P}_2\text{O}_5-\text{CaF}_2$ System 431

*Konstantinos Dimitriadis, Dilshat U. Tulyaganov, and Simeon Agathopoulos*

- 18.1 Introduction 431
- 18.2 State-of-the-Art 432
- 18.3 Design of Novel Compositions in the  $\text{CaO}-\text{MgO}-\text{SiO}_2$  System 435
- 18.4 Synthesis of the Novel Glass-Ceramics and Characterization Methods 437
  - 18.4.1 Glass Synthesis and Thermal Analysis 438
  - 18.4.2 Glass-Ceramics Production and Characterization 439
- 18.5 Properties of the Glass-Ceramic Materials 441
  - 18.5.1 Parent Glass-Ceramic Compositions 441
    - 18.5.1.1 Densification and Crystallization 441
    - 18.5.1.2 Mechanical Properties 445
    - 18.5.1.3 Bioactivity 446
    - 18.5.1.4 General Evaluation of the Parent GCs 1d and 1e 446
  - 18.5.2 Modified Glass-Ceramic Compositions 447
    - 18.5.2.1 Densification and Crystallization 447
    - 18.5.2.2 Mechanical Properties 449
    - 18.5.2.3 Bioactivity 449
    - 18.5.2.4 General Evaluation of the Modified Glass-Ceramics 450
- 18.6 Feasibility of the Application of the Novel Glass-Ceramics in Dental Implantology 451
- 18.7 Concluding Remarks 452  
References 453

## 19 Applications of Bioactive Glasses for Implants in the Ear 459

*Mario Milazzo, Glauco Cristofaro, Stefano Berrettini, and Serena Danti*

- 19.1 Introduction 459
- 19.2 Bioactive Glasses in Otorhinolaryngology: Biological Properties 461
  - 19.2.1 Bioactive Glasses in Otorhinolaryngology 461

- 19.2.2 Antimicrobial Activity 462
- 19.2.3 Tissue Induction and Integration 462
- 19.3 Clinical Applications 463
- 19.3.1 Mastoid Obliteration and Posterior Meatal Wall Reconstruction 463
- 19.3.2 Replacements for the Ossicular Chain 467
- 19.3.3 Cochlear Implants 468
- 19.3.4 Other Uses in the Craniofacial Area 469
- 19.3.4.1 Cranial Defect Repair 469
- 19.3.4.2 Sinonasal Obliteration 469
- 19.3.4.3 Septal Cartilage Repair 470
- 19.3.4.4 Orbital Floor Repair 471
- 19.4 Conclusions and Future Directions 472
- Acknowledgments 472
- References 473

## **20 Bioactive Glass: Soft Tissue Reparative and Regenerative Applications 479**

*Shreyasi Majumdar, Smriti Gupta, and Sairam Krishnamurthy*

- 20.1 Introduction 479
- 20.2 BAGs in Contact with Soft Tissues 480
- 20.2.1 Wound Healing 480
- 20.2.2 Skeletal Muscle, Ligament, and Tendon Regeneration 482
- 20.2.3 Gastrointestinal Tissue Regeneration 486
- 20.2.4 Lung Tissue Engineering 488
- 20.2.5 Cardiac Tissue Engineering 491
- 20.2.6 Ophthalmology 491
- 20.2.7 Stomatology 495
- 20.2.8 Otorhinolaryngology 498
- 20.2.8.1 Otology 498
- 20.2.8.2 Rhinology 500
- 20.2.8.3 Laryngeal Repair 502
- 20.2.9 Urinary Tract Infection 502
- 20.3 Conclusion 506
- References 506

## **21 Bioactive Glasses as Biologically Active Materials for Healing of Skin Wounds 519**

*Tina Mehrabi, Abdorreza S. Mesgar, and Zahra Mohammadi*

- Abbreviations 519
- 21.1 Introduction 519
- 21.2 The Healing Process of Skin Wounds and Wound Care Approaches 520
- 21.3 Overview of Bioactive Glass Structure 521
- 21.4 Metallic, Metalloid, and Nonmetallic Elements: The Main Role Players of Biological Effects of Bioactive Glasses in Human Body 523
- 21.5 The Applications of Bioactive Glasses in Skin Wound Healing 524
- 21.5.1 Can Bioactive Glasses Meet the Requirements of a Hard to Heal Wound to Be Successfully Healed? 525

- 21.5.2 Clinical Studies and Commercial Products 528
- 21.6 Conclusions and Outlook 528
- References 529

## 22 Biocompatible Glasses Applied in Cancer Treatment: Magnetic Hyperthermia and Brachytherapy 537

*Roger Borges, Ana Carolina S. Souza, Luis A. Genova, Joel Machado Jr., Giselle Z. Justo, and Juliana Marchi*

- 22.1 General Aspects of Cancer Molecular Biology 537
  - 22.1.1 Cancer Treatment in the Clinical Practice 538
- 22.2 Bioactive Glasses Applied in Hyperthermia 539
  - 22.2.1 Magnetic Hyperthermia: Introduction and Physics Aspects 539
  - 22.2.2 Biological Effects of Hyperthermia 543
  - 22.2.3 Bioactive Glass-Ceramics Applied in Magnetic Hyperthermia 545
    - 22.2.3.1 Melt-Derived Glass-Ceramics 546
    - 22.2.3.2 Biphasic Glass-Ceramics 547
    - 22.2.3.3 Sol-Gel-Derived Glass-Ceramic 550
  - 22.2.4 Future Perspectives, Open Questions, and Challenges 553
- 22.3 Bioactive Glasses Applied in Brachytherapy 554
  - 22.3.1 Brachytherapy: Classification and Physical Aspects 554
  - 22.3.2 Radiobiology of Brachytherapy for Cancer Treatment 557
    - 22.3.2.1 DNA Repair 558
    - 22.3.2.2 Redistribution in the Cell Cycle 559
    - 22.3.2.3 Repopulation 560
    - 22.3.2.4 Reoxygenation 560
  - 22.3.3 Biocompatible Glasses Applied in Brachytherapy 562
    - 22.3.3.1 Introduction to Radioembolization: Materials and Applications 562
    - 22.3.3.2 Advances in Glass Microspheres for Radioembolization 564
    - 22.3.3.3 Manufacturing Methods of Glass Microspheres 566
    - 22.3.3.4 Bioactive Glasses for Treatment of Bone Cancer by Brachytherapy 567
  - 22.3.4 Challenges and Future Perspective 569
- Acknowledgments 570
- References 570

## 23 Bioactive Glasses with Antibacterial Properties: Mechanisms, Compositions, and Applications 581

*Mostafa Awaid and Ilaria Cacciotti*

- 23.1 Introduction 581
- 23.2 Mechanisms of Antimicrobial Activities 582
- 23.3 Intrinsic Antibacterial Properties of Bioactive Glass Compositions Without Any Specific Bactericidal Ion 584
- 23.4 Strategies to Provide Antimicrobial Properties 584
  - 23.4.1 Addition of Biocidal Metals in the Formulated Compositions 586
    - 23.4.1.1 Bioactive Glasses Doped with Silver 592
    - 23.4.1.2 Bioactive Glasses Doped with Copper 592
    - 23.4.1.3 Bioactive Glasses Doped with Zinc 593

23.4.1.4	Bioactive Glasses Doped with Strontium	594
23.4.1.5	Bioactive Glasses Doped with Gallium	594
23.4.1.6	Bioactive Glasses Doped with Fluoride	595
23.4.1.7	Bioactive Glasses Doped with Cerium	595
23.4.2	Bio-glasses Loaded with Antibiotics	595
23.5	Applications of Antimicrobial Bio-glasses	596
23.6	Concluding Remarks and Future Perspectives	602
	References	603

<b>Index</b>	<b>615</b>
--------------	------------



## Preface

Bioactive glasses and glass-ceramics are a versatile class of biocompatible materials that have an astonishing impact in biomedicine. There is a long successful history in the synthesis, characterization, and utilization of these man-made materials. Generally, the expertise of researchers and scientists working in materials science, tissue engineering, biology, and medicine are required for producing the “best” glass and glass-ceramic formulations with optimized properties in favor of tissue repair and regeneration.

The first and foremost application of such biomaterials is addressed to treat hard tissue damages and injuries because of their inherent characteristics such as stiffness and bone-bonding ability. Bioactive glasses were first invented by Professor Larry L. Hench at the University of Florida more than half a century ago in 1969. The original bioactive glass, designed in a silicate system with a composition of  $45\text{SiO}_2\text{-}24.5\text{Na}_2\text{O-}24.5\text{CaO-}6\text{P}_2\text{O}_5$  (wt%), was initially developed to meet the need for bone replacement of injured soldiers returned from the Vietnam War. Since then, a huge number of other compositions and bioactive glass-based products have been proposed and introduced into the market for managing hard tissue diseases and disorders. PerioGlas® and BonAlive® are two well-known synthetic bone grafts based on bioactive glasses with admirable success in the clinic. Over the last couple of decades, other types of bioactive glasses, including phosphate- and borate-based glasses, have been developed and applied for treating a wide range of tissue damages, including soft tissue injuries. In this regard, RediHeal™, a borate-based bioactive glass, is currently being used for managing wounds in animals and is awaiting for getting Food and Drug Administration (FDA) approval for practicing in humans suffering from slow-healing wounds (e.g. diabetic foot ulcers).

The main advantages of bioactive glasses are associated with their exceptional versatility in terms of composition–property relationships, controlled crystallized that can dictate the physicochemical and mechanical characteristics, and inherent ability to attach to both hard and soft tissues. Specifically, the ability to bond to living bone is related to the formation of a nano-crystalline hydroxyapatite layer, similar to bio-apatites, on the surface of bioactive glasses after exposure to body fluids. From a biological point of view, bioactive glasses cause no short- and long-term adverse effects on human cells, tissues, and organs; therefore, they are generally identified as biocompatible substances in biomedicine. Bioactive glasses are considered the osteoconductive and osteoinductive materials as they can provide a suitable substrate for adhesion and growth of bone-forming cells as well as induce osteoprogenitor cells to differentiate toward osteogenic lineages. In addition, bioactive glasses exhibit antibacterial, anti-inflammatory, and pro-angiogenic activities *in vitro* and *in vivo*. On this matter, a broad range of therapeutic ions (e.g. silver  $[\text{Ag}^+]$  and copper  $[\text{Cu}^{2+}]$ ) are incorporated into the basic compositions of bioactive glasses to improve their biological performances imparting extra-functionalities, like antibacterial and pro-angiogenic properties. Indeed,

the release of therapeutic ions from bioactive glasses allows their usage as drug delivery vehicles for biomedical strategies. Recently published scientific reports emphasize the therapeutic capacity of bioactive glasses in battling against different types of cancers, especially those associated with hard tissues. On this point, mesoporous bioactive glasses possess an added value since their inherently nano-textured structure also provides a suitable platform for the incorporation and controlled delivery of a wide range of anti-cancer drugs to desired sites. With the advent of three-dimensional (3D) printing or additive manufacturing, the fabrication of 3D constructs based on or containing bioactive glasses and glass-ceramics offers a plethora of advantages, including improved mechanical strength and biological performance.

The present book aims to provide an updated understanding of biocompatible glasses and glass-ceramics based on current evidence in the literature and draw their future in the fields of biomaterials and tissue engineering. Basic aspects of bioactive glasses and glass-ceramics along with their fabrication routes and the latest processing strategies (e.g. additive manufacturing, laser treatments) are well-discussed from a materials science point of view. Besides, the biological effects of glasses and glass-ceramics have been considered on the living systems (*in vitro* and *in vivo*) as well as the current market needs and clinical challenges. The pros and cons of mesoporous bioactive glasses are argued in terms of drug delivery systems in relevant chapters. From a tissue engineering point of view, the regenerative capacity of different types of bioactive glasses and glass-ceramics has been reviewed in connection with hard (e.g. bone and teeth) and soft (e.g. skin) tissue healing. Moreover, hopes raised by these synthetic biomaterials in the treatment of malignancies have been well explored to shed light on their possible roles in the next-generation therapies. We hope that the present book is beneficial for the potential readership working in a broad community, who has a scientific background ranging from materials science and bioengineering to medicine and tissue engineering.

Politecnico di Torino, Turin, Italy  
Mashhad University of Medical Sciences, Mashhad, Iran  
March 26, 2022

*Francesco Baino*  
*Saeid Kargozar*

## List of Contributors

### ***Simeon Agathopoulos***

Department of Materials Science and Engineering  
University of Ioannina  
Ioannina  
Greece

### ***William Alles***

Kazuo Inamori School of Engineering  
Alfred University  
Alfred, NY  
USA

### ***Felipe Arias-González***

LaserON Laser Applications Research Group  
Research Center in Technologies, Energy and Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Applied Physics Department  
EEI, University of Vigo  
Vigo  
Spain

### ***Mostafa Awaid***

Department of Engineering  
University of Rome “Niccolò Cusano”, INSTM  
RU  
Rome  
Italy

### ***Francesco Baino***

Institute of Materials Physics and Engineering  
Department of Applied Science and Technology (DISAT)  
Politecnico di Torino  
Torino  
Italy

### ***Sadaf Batool***

School of Chemical and Materials Engineering (SCME)  
National University of Sciences and Technology (NUST)  
Islamabad  
Pakistan

### ***Stefano Berrettini***

Laboratory of Temporal Bone Dissection and Otologic Tissue Engineering (OtoLab)  
Department of Surgical, Medical, Molecular Pathology and Emergency Medicine  
University of Pisa  
Pisa  
Italy

### ***Aldo R. Boccaccini***

Department of Materials Science and Engineering  
Institute of Biomaterials  
University of Erlangen-Nuremberg  
Erlangen  
Germany

**Roger Borges**

Centro de Ciências Naturais e Humanas  
Universidade Federal do ABC  
Santo André  
Brazil

**Mohamed Boutinguiza**

LaserON Laser Applications Research Group  
Research Center in Technologies, Energy and  
Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Applied Physics Department  
EEI, University of Vigo  
Vigo  
Spain

**Delia S. Brauer**

Otto Schott Institute of Materials Research  
Faculty of Chemistry and Earth Sciences  
Friedrich Schiller University  
Jena  
Germany

**Ilaria Cacciotti**

Department of Engineering  
University of Rome “Niccolò Cusano”  
INSTM RU  
Rome  
Italy

**Rafael Comesaña**

LaserON Laser Applications Research Group  
Research Center in Technologies, Energy and  
Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Department of Materials Engineering  
Applied Mechanics and Construction  
EEI, University of Vigo  
Vigo  
Spain

**Glauco Cristofaro**

Division of Otorhinolaryngology (ORL)  
Arcispedale di “Santa Maria Nuova”  
Florence  
Italy

and

Laboratory of Temporal Bone Dissection and  
Otologic Tissue Engineering (OtoLab)  
Department of Surgical, Medical, Molecular  
Pathology and Emergency Medicine  
University of Pisa  
Pisa  
Italy

**Serena Danti**

Laboratory for Atomistic and Molecular  
Mechanics (LAMM)  
Massachusetts Institute of Technology  
Cambridge, MA  
USA

and

University of Pisa Research Unit  
National Interuniversity Consortium of  
Materials Science and Technology (INSTM)  
Florence  
Italy

and

Laboratory of Temporal Bone Dissection and  
Otologic Tissue Engineering (OtoLab)  
Department of Surgical, Medical, Molecular  
Pathology and Emergency Medicine  
University of Pisa  
Pisa  
Italy

and

Department of Civil and Industrial  
Engineering  
University of Pisa  
Pisa  
Italy

***Durgalakshmi Dhinasekaran***

Department of Medical Physics  
Anna University  
Chennai  
India

***Konstantinos Dimitriadis***

Department of Materials Science and  
Engineering  
University of Ioannina  
Ioannina  
Greece

and

Division of Dental Technology  
Department of Biomedical Sciences  
University of West Attica  
Athens  
Greece

***Ahmed El-Fiqi***

Glass Research Department  
Advanced Materials Technology and Mineral  
Resources Research Institute  
National Research Centre  
Cairo 12622  
Egypt

***Elisa Fiume***

Institute of Materials Physics and Engineering  
Department of Applied Science and  
Technology (DISAT)  
Politecnico di Torino  
Torino  
Italy

***Jessica Fletcher***

Kazuo Inamori School of Engineering  
Alfred University  
Alfred, NY  
USA

***Qiang Fu***

Science and Technology Division  
Corning Inc.  
Corning, NY  
USA

***Luis A. Genova***

Centro de Ciência e Tecnologia dos Materiais  
Instituto de Pesquisas Energéticas e Nucleares  
São Paulo  
Brazil

***Smriti Gupta***

Neurotherapeutics Laboratory  
Department of Pharmaceutical Engineering  
and Technology  
Indian Institute of Technology (Banaras Hindu  
University)  
Varanasi  
India

***Leena Hupa***

Johan Gadolin Process Chemistry Centre  
Faculty of Science and Technology  
Åbo Akademi University  
Turku  
Finland

***Zakir Hussain***

School of Chemical and Materials Engineering  
(SCME)  
National University of Sciences and  
Technology (NUST)  
Islamabad  
Pakistan

**Kanwal Ilyas**

Department of Materials Science and Engineering  
Institute of Biomaterials  
University of Erlangen-Nuremberg  
Erlangen  
Germany

**Giselle Z. Justo**

Departamento de Bioquímica  
Universidade Federal de São Paulo  
São Paulo  
Brazil

**Saeid Kargozar**

Tissue Engineering Research Group (TERG)  
Department of Anatomy and Cell Biology,  
School of Medicine  
Mashhad University of Medical Sciences  
Mashhad  
Iran

**Timothy James Keenan**

Kazuo Inamori School of Engineering  
Alfred University  
Alfred, NY  
USA

**Sairam Krishnamurthy**

Neurotherapeutics Laboratory  
Department of Pharmaceutical Engineering  
and Technology  
Indian Institute of Technology (Banaras Hindu  
University)  
Varanasi  
India

**Anuj Kumar**

School of Chemical Engineering  
Yeungnam University  
Gyeongsan  
Republic of Korea

**Usman Liaqat**

School of Chemical and Materials Engineering  
(SCME)  
National University of Sciences and  
Technology (NUST)  
Islamabad  
Pakistan

**Nina C. Lindfors**

Department of Hand Surgery  
Helsinki University Hospital  
Helsinki  
Finland

and

Department of Surgery  
Helsinki University  
Helsinki  
Finland

**Fernando Lusquiños**

LaserON Laser Applications Research Group  
Research Center in Technologies  
Energy and Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Applied Physics Department  
EEI, University of Vigo  
Vigo  
Spain

**Joel Machado Jr.**

Departamento de Ciências Biológicas  
Universidade Federal de São Paulo  
Diadema  
Brazil

**Shreyasi Majumdar**

Neurotherapeutics Laboratory  
 Department of Pharmaceutical Engineering  
 and Technology  
 Indian Institute of Technology (Banaras Hindu  
 University)  
 Varanasi  
 India

**Juliana Marchi**

Centro de Ciências Naturais e Humanas  
 Universidade Federal do ABC  
 Santo André  
 Brazil

**Jonathan Massera**

Faculty of Medicine and Health Technology  
 Tampere University  
 Tampere  
 Finland

**John C. Mauro**

Department of Materials Science and  
 Engineering  
 The Pennsylvania State University  
 University Park, PA  
 USA

**Tina Mehrabi**

Biomaterials Laboratory, Division of  
 Biomedical Engineering  
 Department of Life Science Engineering  
 Faculty of New Sciences and Technologies  
 University of Tehran  
 Tehran  
 Iran

**Abdorrezza S. Mesgar**

Biomaterials Laboratory, Division of  
 Biomedical Engineering  
 Department of Life Science Engineering  
 Faculty of New Sciences and Technologies  
 University of Tehran  
 Tehran  
 Iran

**Carla Migneco**

Institute of Materials Physics and Engineering  
 Department of Applied Science and  
 Technology (DISAT)  
 Politecnico di Torino  
 Torino  
 Italy

**Mario Milazzo**

Laboratory for Atomistic and Molecular  
 Mechanics (LAMM)  
 Massachusetts Institute of Technology  
 Cambridge, MA  
 USA

University of Pisa Research Unit  
 National Interuniversity Consortium of  
 Materials Science and Technology (INSTM)  
 Florence  
 Italy

and

Department of Civil and Industrial  
 Engineering University of Pisa  
 Pisa  
 Italy

**Zahra Mohammadi**

Biomaterials Laboratory, Division of  
 Biomedical Engineering  
 Department of Life Science Engineering  
 Faculty of New Sciences and Technologies  
 University of Tehran  
 Tehran  
 Iran

**Maziar Montazerian**

Department of Materials Engineering  
 Northeastern Laboratory for Evaluation and  
 Development of Biomaterials (CERTBIO)  
 Federal University of Campina Grande  
 Campina Grande  
 Brazil

***Araceli de Pablos Martín***

Otto Schott Institute of Materials Research  
Faculty of Chemistry and Earth Sciences  
Friedrich Schiller University  
Jena  
Germany

***Juan Pou***

LaserON Laser Applications Research Group  
Research Center in Technologies  
Energy and Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Applied Physics Department  
EEI, University of Vigo  
Vigo  
Spain

***Félix Quintero***

LaserON Laser Applications Research Group  
Research Center in Technologies  
Energy and Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Applied Physics Department  
EEI, University of Vigo  
Vigo  
Spain

***Antonio Riveiro***

LaserON Laser Applications Research Group  
Research Center in Technologies  
Energy and Industrial Processes  
CINTECX  
University of Vigo  
Vigo  
Spain

and

Department of Materials Engineering  
Applied Mechanics and Construction  
EEI, University of Vigo  
Vigo  
Spain

***Daniel J. Sola***

Laboratorio de Óptica  
Centro de Investigación en Óptica y Nanofísica  
(CIOyN)  
Campus Espinardo,  
Universidad de Murcia  
Murcia  
Spain

and

Aragonese Foundation for Research and  
Development (ARAID)  
Government of Aragon  
Zaragoza  
Spain

***Ana Carolina S. Souza***

Centro de Ciências Naturais e Humanas  
Universidade Federal do ABC  
Santo André  
Brazil

***Dilshat U. Tulyaganov***

Department of Natural–Mathematical Sciences  
Turin Polytechnic University in Tashkent  
Tashkent  
Uzbekistan

- synthesis process 94
  - synthesization 93–96
  - sol–gel-derived copper-doped mesoporous bioactive glass 494
  - sol–gel-derived glass CaPSiO<sub>2</sub> antibacterial action 584
  - sol–gel-derived glass-ceramics
    - categories of 550
    - magnetic and biological characterization of 550
    - MBGC scaffolds 552–553
    - mesoporous MBGC production 551, 552
  - sol–gel process
    - coating methods 300
    - fabrication methods 152
  - solid freeform fabrication (SFF) techniques 154
    - fused deposition modeling 133–134
    - ink-jet printing 134–135
    - robocasting 136–138
    - selective laser sintering 130–132
    - stereolithography 132–133
    - three-dimensional printing 135–136
  - S53P4 bioglass 398
    - bone growth into 51
    - bone infections, treatment 43–44
    - composition, *in vitro* antibacterial properties of 584
    - compositions 47–48
    - efficacy and safety of 465
    - fiber-reinforced calvarial implants 44–46
    - granules, orthopedics 41–43
    - weight-bearing applications 49–50
  - S53P4 disc implants 501
  - species-pore size 249
  - specific absorption rate (SAR) 542
  - specific surface area (SSA) 179
  - S53P4 plates and granules 500
  - Staphylococcus aureus* 44
  - stereolithography 132–133
  - Stimuli-responsive hydrogel swelling 101
  - Stöber synthesis 177–178
  - Stokes–Einstein/Eyring equation 8
  - Stokes/Eyring–Einstein relationship (SEE) 386–388
  - stomatology 495–498
  - String Method Car–Parrinello approach 382
  - strontium (Sr) 213–214, 232
  - strontium-doped BGs 594
  - succinyl chitosan (SCS) 101
  - superficial brachytherapy 555
  - superparamagnetic iron oxide nanoparticles (SPIONs) 554
  - superparamagnetism 541
  - surface coating 304
  - surface crystallization 9
  - surface modification of BGs 277–279
  - synthetic polymers 295, 296, 304, 305
- t**
- teicoplanin (TEC) 82
  - tendon regeneration 486
  - ternary CaO–MgO–SiO<sub>2</sub> system 435–437
  - therapeutic drug delivery systems 244
  - therapeutic species, BGs
    - biomolecule release 245–246
    - drug release
      - antibacterial drugs 241–242
      - small therapeutic drugs for diseases 243–245
      - species 238–241
    - dual/multi-species release 246–247
    - loaded species 247
  - MBG-based carriers
    - compositions 250–251
    - pore structure 249
    - species-pore size 249
    - surface modification 251
  - platform materials 227–229
  - therapeutic ion release
    - bioactive ion delivery (*see* bioactive ion delivery)
    - constitutive therapeutic ions 229–230
    - ion release profiles (*see* ion release profiles)
- TheraSphere 563
- thermogravimetric analysis (TGA) 302
  - third-generation bioglass 581
  - 3D printed BAG auricle 472
  - three-dimensional printing (3DP) technique 106–110, 135–136
  - Ti6Al4V alloy
    - bioactive glass coating on 311, 312
    - calcium phosphate coating on 311, 313
    - 45S5 BG and S520 BG wetting angle on 322
  - Ti6Al4V dental implants, disadvantages of 432

- time-temperature-transformation curves (TTT curves) 9
- tissue engineering (TE) 96  
 anticancer and cardiovascular 282–283  
 borate glass 73  
 hierarchical pores of 228  
 hydrogel method 98–104
- tissue regeneration 397  
 bioactive glass-based scaffolds for 399–401  
 cell cycle in 404–407  
 elements role in  
 cerium 420  
 copper and cobalt 420  
 iron 420  
 lithium and strontium 419–420  
 silver 421  
 zinc 420  
*in vitro/in vivo* evaluation of BGs 408–411
- titanium nitride (TiN) coating 294
- TORP, Bioverit II based 468
- trabecular microstructure scaffolds 400
- Transmission electron microscopy (TEM) 303
- transparent glass-ceramics 1
- tulsi *see Ocimum sanctum*
- tumor necrosis factor  $\alpha$  (TNF- $\alpha$ ) 81
- turmeric extract 268
- Turnbull approximations 387
- tympanic membrane reconstruction 463–464
- tympanoplasty 498
- type-I collagen 404
- u**
- ultrasonic-coupled sol-gel synthesis 176–177
- ultrathin MBG hollow fibers 596
- urinary tract infections (UTIs) 502, 506
- v**
- vascular endothelial growth factor A (VEGFA) 234, 245
- vascular endothelial growth factors (VEGF) 48, 204
- vital pulp therapy (VPT) 495
- volume crystallization 9
- volumetric muscle loss (VML) 483
- w**
- water adsorption modes 381, 382
- Weibull distribution 159
- weight-bearing bones 49–50
- Wilson-Frenkel theory (WFT) 386
- wound care approach 520–521
- wound healing 281–282, 417, 480–482, 497, 519 *see also* skin wound healing
- x**
- X-ray, lateral tibial plateau fracture 42
- y**
- <sup>90</sup>Y-bioactive glass 568
- <sup>90</sup>Y TheraSphere 565, 566
- yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) 434
- yttrium-doped bioactive glass (YBGs) 383
- z**
- zinc (Zn) 214
- zinc (Zn) bioactive glass hydrogels 102
- zinc (Zn)-doped BGs 593
- zinc-doped bioactive glass (ZBG) 101
- zinc (Zn)-doped calcium phosphate glass 595
- zinc-doped phosphate-based bioactive glass (Zn-PBG) 502
- zinc ferrite glass-ceramics power loss 547, 548
- zinc ferrite's magnetic crystal 547
- Zingiberaceae 264
- zirconia  
 ceramic implants, chemical degradation of 434  
 dental implant 497



