

# Contents

|          |                                                                                                                    |           |
|----------|--------------------------------------------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Research Background</b>                                                                                         | <b>1</b>  |
| 1.1      | Introduction                                                                                                       | 1         |
| 1.2      | Synthetic Methodologies and Structures of Mesoporous Materials                                                     | 2         |
| 1.2.1    | Formation Mechanism of Mesoporous Materials                                                                        | 2         |
| 1.2.2    | Structures of Mesoporous Materials                                                                                 | 3         |
| 1.3      | Biomedical Applications of Mesoporous Materials                                                                    | 6         |
| 1.3.1    | Mesoporous Materials for Drug Loading and Sustained Release                                                        | 8         |
| 1.3.2    | Mesoporous Materials for Controlled Drug Releasing                                                                 | 8         |
| 1.3.3    | Mesoporous Materials for Photodynamic Therapy                                                                      | 9         |
| 1.3.4    | Mesoporous Materials for Synergistic Therapy                                                                       | 12        |
| 1.3.5    | MSNs for Targeted Drug Delivery                                                                                    | 13        |
| 1.3.6    | Mesoporous Materials for Theranostic Applications                                                                  | 14        |
| 1.4      | The Development Trends of Mesoporous Materials                                                                     | 21        |
| 1.5      | Significance of this Thesis                                                                                        | 21        |
|          | References                                                                                                         | 22        |
| <b>2</b> | <b>Synthesis of Hollow Mesoporous Silica Nanoparticles by Silica-Etching Chemistry for Biomedical Applications</b> | <b>31</b> |
| 2.1      | Introduction                                                                                                       | 31        |
| 2.2      | Experimental Section                                                                                               | 32        |
| 2.2.1    | Synthesis of HMSNs Based on SDSE Strategy                                                                          | 32        |
| 2.2.2    | Synthesis of HMSNs by Chemical Etching in Ammonia Solution                                                         | 33        |
| 2.2.3    | Study of the Formation Mechanism of HMSNs                                                                          | 33        |
| 2.2.4    | Synthesis of Multifunctional Rattle-Type HMSNs Based on SDSE Strategy                                              | 33        |
| 2.2.5    | Hemolytic Effect Evaluation                                                                                        | 34        |

|          |                                                                                                                    |           |
|----------|--------------------------------------------------------------------------------------------------------------------|-----------|
| 2.2.6    | In Vitro DOX-Loading into HMSNs                                                                                    | 34        |
| 2.2.7    | MTT Evaluation of the Cytotoxicity of HMSNs<br>and DOX-HMSNs                                                       | 35        |
| 2.3      | Results and Discussion                                                                                             | 35        |
| 2.3.1    | Synthesis and Characterization of HMSNs                                                                            | 35        |
| 2.3.2    | Synthesis of Multifunctional M@mSiO <sub>2</sub> Nanorattles                                                       | 40        |
| 2.3.3    | HMSNs for Anticancer Drug Delivery                                                                                 | 43        |
| 2.4      | Conclusions                                                                                                        | 44        |
|          | References                                                                                                         | 45        |
| <b>3</b> | <b>Multifunctional Mesoporous Silica Nanoparticles<br/>for Theranostics of Cancer</b>                              | <b>47</b> |
| 3.1      | Introduction                                                                                                       | 47        |
| 3.2      | Experimental Section                                                                                               | 48        |
| 3.2.1    | Synthesis of Fe <sub>3</sub> O <sub>4</sub> @mSiO <sub>2</sub>                                                     | 48        |
| 3.2.2    | Synthesis of Gd-Si-DPTA-Au@mSiO <sub>2</sub>                                                                       | 49        |
| 3.2.3    | Blood Compatibility of Fe <sub>3</sub> O <sub>4</sub> @mSiO <sub>2</sub>                                           | 49        |
| 3.2.4    | In Vitro Cytotoxicity of Fe <sub>3</sub> O <sub>4</sub> @mSiO <sub>2</sub> Nanocapsules                            | 50        |
| 3.2.5    | Drug-Loading and Anticancer Efficiency                                                                             | 50        |
| 3.2.6    | CLSM Observations of the Cell Internalization<br>of Fe <sub>3</sub> O <sub>4</sub> @mSiO <sub>2</sub> Nanocapsules | 50        |
| 3.2.7    | Bio-TEM Observations                                                                                               | 51        |
| 3.2.8    | In Vitro and In Vivo MR Imaging                                                                                    | 51        |
| 3.2.9    | Dark-Field Microscopic Labeling of HeLa Cancer Cells                                                               | 51        |
| 3.3      | Results and Discussion                                                                                             | 52        |
| 3.3.1    | Synthesis of Characterization of Fe <sub>3</sub> O <sub>4</sub> @mSiO <sub>2</sub>                                 | 52        |
| 3.3.2    | Magnetic Fe <sub>3</sub> O <sub>4</sub> @mSiO <sub>2</sub> for MRI and Anticancer<br>Drug Delivery                 | 53        |
| 3.3.3    | Synthesis of Gd-Si-DTPA-Grafted Au@mSiO <sub>2</sub><br>for Biomedical Applications                                | 60        |
| 3.4      | Conclusions                                                                                                        | 63        |
|          | References                                                                                                         | 63        |
| <b>4</b> | <b>Hollow Mesoporous Silica Nanoparticles for Ultrasound-Based<br/>Cancer Diagnosis and Therapy</b>                | <b>65</b> |
| 4.1      | Introduction                                                                                                       | 65        |
| 4.2      | Experimental Section                                                                                               | 66        |
| 4.2.1    | Material Synthesis                                                                                                 | 66        |
| 4.2.2    | In Vitro MRI Evaluation                                                                                            | 67        |
| 4.2.3    | Ex Vivo Evaluation Toward the HIFU Synergistic<br>Effect of IMNCs, PFH-IMNCs, MCNCs,<br>and PFH-MCNCs              | 67        |
| 4.2.4    | CLSM Observation of Intracellular Uptake<br>and Location of RITC-MCNCs                                             | 68        |

|       |                                                                                                                                    |    |
|-------|------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.2.5 | In Vivo Evaluation of the HIFU Synergistic Effect of IMNCs, PFH-IMNCs, MCNCs, and PFH-MCNCs Against Rabbit VX2 Xenograft . . . . . | 68 |
| 4.3   | Results and Discussion. . . . .                                                                                                    | 69 |
| 4.3.1 | IMNCs as the Synergistic Agents for HIFU Ablation . . . . .                                                                        | 69 |
| 4.3.2 | MCNCs for MRI-Guided HIFU Cancer Surgery . . . . .                                                                                 | 71 |
| 4.4   | Conclusions . . . . .                                                                                                              | 82 |
|       | References . . . . .                                                                                                               | 82 |
| 5     | Summary and Outlook . . . . .                                                                                                      | 85 |
| 5.1   | Summary . . . . .                                                                                                                  | 85 |
| 5.2   | Outlook. . . . .                                                                                                                   | 86 |